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Improving Microgrid stability by integrating renewable energies (Solar Energy) and ESS

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Dedication

I have a great pleasure to dedicate this modest work to my Beloved Mother and my Dear Father to my Dear Sisters, Little Brother, to all my Friends, to all my Teachers from my first year of primary school to my last year of university

Hilal Ziani

Dedication

I have a great pleasure to dedicate this modest work to our Beloved MOM and DAD who have been our source of inspiration and gave me strength when thought of giving up.

To my Dear Brothers, Sisters, Aunts whose unwavering love and support have carried me through, and have been my guiding light and my source of strength, in every challenge I faced, you were by my side, giving me hope.

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Abstract

This report presents a study on improving the system stability of a micro-grid while satisfying the load demand through the integration of renewable energies, specifically solar energy, along with an energy storage system. The objective of this project is to explore the effectiveness of incorporating renewable energy sources and energy storage in enhancing the stability and reliability of micro-grid systems. The proposed approach involves the integration of solar energy as a primary renewable energy source in the micro-grid system. Solar panels harness solar irradiation to generate electricity, contributing to the overall power supply. Additionally, an energy storage system, such as batteries, is implemented to store surplus energy during periods of high solar generation and supply it during peak demand or low generation periods. The integration of these components aims to improve the system's stability by balancing power supply and demand.

Furthermore, the report presents simulation results and performance analysis of the proposed system. Key parameters, such as system stability, power quality, and load demand satisfaction, are evaluated under different operating conditions and scenarios. The analysis provides insights into the effectiveness of the integrated renewable energy and energy storage system in improving system stability and meeting load demand requirements

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List of Abbreviations

PV: Photovoltaic

CHP: Combined heat and power

MW: Megawatts

DER: Distributed energy resources

EESS: Electrical Energy Storage System

AC: Alternating Current

DC: Direct Current

MG: Microgrid

GHI: Global horizontal irradiation

I: Current

I_{Ph}**:** Photo current

I_{Sh}**:** Short Circuit Current

Rs: Series resistance

R_{sh}**:** Shunt resistance

$T_{Ref:}$ Reference temperature

A: Diode quality factor

E_G**:** Bang-gap energy

I_{RS}**:** Reverse saturation current

V: Voltage

V_{OC}**:** Open Circuit Voltage

Vt: Thermalvoltage

MPP: Maximum Power Point

I_{MPP}**:** Maximum Power Point Current

V_{MPP}**:** Maximum Power Point Voltage

I_{PV}**:** Photovoltaic Current

W: Watts

Wp: Peak Watts

FF: Fill Factor

%eff: Percent efficiency

RES: Renewable energy sources

ESS: Electrical Energy Storage System

SOC: state of charge

NREL: National Renewable Energy Laboratory

NPC: Net Present Cost

LCOE: Levelized Cost of Energy

General Introduction

Microgrids represent a significant advancement in the quest for sustainable and reliable energy systems. As energy demands continue to rise, integrating renewable energy sources like photovoltaic (PV) systems becomes increasingly crucial. This project report aims to explore the various facets of microgrids and their components, with a particular focus on PV systems and their integration within microgrids.

This project focus on the simulation of microgrid system integrated with solar energy, and an energy storage system, the approach involves harnessing solar irradiation with solar panels as the primary renewable energy source and utilizing an energy storage system to store excess energy during high solar generation periods and supply it during peak demand or low generation periods. The primary objective is to improve the stability and reliability of micro-grid systems while meeting load demand. The modeling and simulation of the entire system have been employed using the MATLAB/Simulink environment. This comprehensive simulation enables us to analyze and evaluate the performance of the micro-grid under different operating conditions.

The first chapter provides a detailed overview of microgrids, discussing their operational modes, classifications, characteristics, and components, laying the groundwork for understanding their significance in modern power systems. Chapter two focuses on photovoltaic (PV) systems, elucidating their role in enhancing power system stability and covering technical aspects such as solar cell operation and various types of PV cells. In the third chapter, a comprehensive simulation of a small-scale microgrid is conducted using Simulink, evaluating different configurations involving power grid, PV, and battery systems under diverse load conditions, yielding insights into hybrid system effectiveness in managing residential loads. The final chapter extends the analysis by utilizing HOMER software to simulate a hybrid energy system comprising PV panels, batteries, and a diesel generator to cater to a community load over a 15-year period in Boumerdes, Algeria.

Through this structured approach, the report aims to provide a thorough understanding of microgrids and hybrid energy systems, offering practical insights and recommendations for their implementation.

CHAPTER 1: *INTRODUCTION TO MICROGRIDS*

1.1 Introduction

The demand for conventional energy derived from fossil fuels has witnessed a significant surge in recent years, driven by globalization, technological advancements, and rapid expansion across various sectors. However, reliance on conventional energy sources poses considerable environmental risks and comes at a substantial cost. Consequently, nations worldwide are actively seeking innovative, cost-effective, and sustainable alternatives to meet their energy needs.

While renewable energy sources such as wind and hydropower offer promising solutions, their effective harnessing and integration into existing infrastructure present significant challenges. To address these challenges, the integration of renewable energy systems with microgrid technology has emerged as a viable approach. Microgrid technology facilitates the optimal utilization of distributed energy resources, providing greater resilience and efficiency in power generation and distribution.

Overcoming numerous obstacles, microgrid technology has gained widespread acceptance and adoption, enabling the implementation of sophisticated energy management strategies. Furthermore, advancements in smart grid concepts have further enhanced the functionality and performance of power networks, paving the way for more efficient and sustainable energy solutions.

In summary, the integration of renewable energy systems with microgrid technology represents a pivotal step towards achieving energy sustainability and resilience. By harnessing the potential of dispersed energy resources and leveraging innovative energy management strategies, nations can transition towards a more sustainable and environmentally friendly energy landscape.

1.2 Distributed generation

Distributed generation refers to the production of electricity at or near the point of use, utilizing technologies such as combined heat and power (CHP) and solar panels. These systems are situated closer to the loads they serve, offering enhanced flexibility, modularity, and decentralization. Despite typically having a capacity of 10 megawatts (MW) or less, they play a crucial role in modern energy distribution.

Utilizing renewable energy sources is a hallmark of distributed generation, aligning with the growing importance of sustainability in electricity distribution. These sources include geothermal, biomass, solar, wind, and small hydropower, contributing to a cleaner and more environmentally friendly energy landscape.

Integration with smart grid systems enables the management and coordination of distributed energy resources (DER) through an interface. This capability allows for efficient monitoring and control, optimizing system performance and responsiveness to grid conditions.

Distributed generation and storage solutions offer several benefits, including the aggregation of energy from multiple sources and the reduction of environmental impacts. By diversifying energy sources and minimizing reliance on centralized power plants, they enhance supply security and resilience. Additionally, by generating electricity closer to the point of consumption, they mitigate transmission losses, leading to increased efficiency and reliability in energy distribution.

1.3 Smart grid

Smart grids represent the evolution of electricity networks, leveraging digital technologies, sensors, and advanced software to optimize the matching of electricity supply and demand in real-time, thus minimizing costs and ensuring grid stability and reliability.

As the global energy landscape shifts towards cleaner sources, such as wind and solar, there is a corresponding surge in electricity demand and a growing need for efficient grid management. Smart grid technologies play a pivotal role in managing this transition, enabling the integration of variable renewables while reducing the requirement for costly grid infrastructure upgrades.

Furthermore, smart grid technologies enhance the resilience and reliability of electricity grids, bolstering their ability to withstand disruptions and adapt to changing conditions. By facilitating greater automation, monitoring, and control capabilities, smart grids empower utilities and consumers alike to make informed decisions and optimize energy usage. [1]

1.4 Microgrids

A microgrid represents a cluster of interconnected power supplies, loads, and energy storage systems that collaborate to reliably deliver energy. It can either operate independently or be connected to the main grid. Essentially, a microgrid serves as a scaled-down version of the utility power system, offering safer, more dependable, and efficient power, especially during grid outages[2].

Microgrids encompass three key aspects: interconnection and distribution, cooperation and control, and independence from the main grid. These elements are integral to the functionality and significance of microgrids within modern power systems. Interconnection and distribution facilitate the seamless integration of renewable and eco-friendly energy sources, contributing to sustainability and environmental conservation efforts. Cooperation and control mechanisms enable efficient management of energy resources, optimizing performance and responsiveness to changing demand. Independence from the main grid enhances the resilience and reliability of microgrids, making them indispensable for sustainable energy solutions. By providing a decentralized and adaptive approach to energy distribution, microgrids play a crucial role in ensuring energy security and mitigating the impacts of grid disruptions.

Power generation technologies with almost zero emissions offer a significant opportunity for reducing environmental impact while meeting energy demands. By fostering cooperation between these sources, there's potential to substantially decrease the energy cost per unit, stimulating a thriving market that can bolster the local economy and generate more jobs. Moreover, independence from the main grid enables the provision of energy to isolated areas. Microgrids can be implemented in diverse settings, ranging from small buildings to smart neighborhoods, urban locations to islands, and even in unconventional spaces such as elevators, aircraft, and ships [3] [4].

1.5 Microgrid operation modes

Microgrids can be classified into two main categories: off-grid and grid-connected, each offering a variety of configurations to suit different energy needs and contexts.

1.5.1 Off-Grid

Off-grid microgrids are deployed in areas where there is high demand for electricity but no access to a large-scale electrical grid. In this mode, the microgrid operates independently of the main grid and can function in what is known as "island mode." During island mode, part or all of the microgrid is disconnected from the main grid and relies solely on an Electrical Energy Storage System (EESS) for power supply, also referred to as "backup mode." Renewable energy sources primarily power off-grid microgrids, with occasional use of diesel generators as backup systems. [5] [6]

Off-grid microgrids are particularly suitable for remote areas where the transmission and distribution of power from centralized sources are impractical and costly. They provide a viable solution for rural electrification projects in smaller islands and isolated regions, offering access to reliable and sustainable electricity.

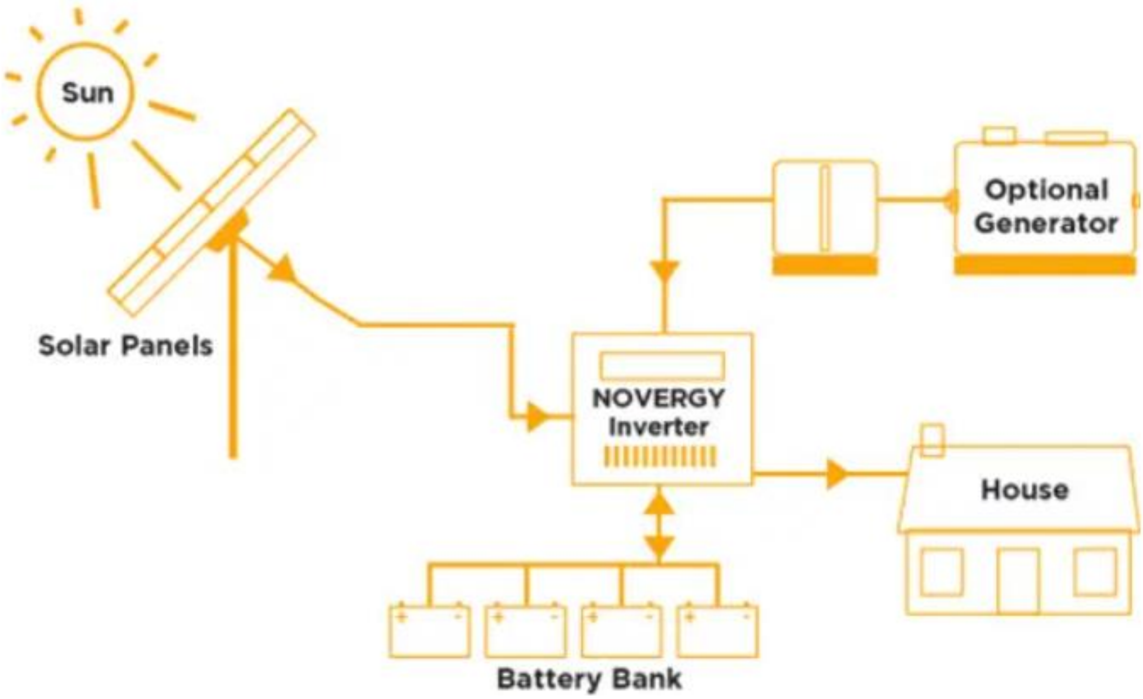

Figure 1.1 Off-grid architecture

1.5.2 Grid-Connected

Grid-connected mode describes the operation of a microgrid that is connected to the utility grid and operates simultaneously with it. In this mode, the microgrid remains synchronized and connected to the wider grid system, with the utility company managing the overall delivery of electricity to the Point of Common Coupling.

A grid-connected microgrid typically operates in synchrony with the conventional grid using a synchronizer. However, under certain circumstances, such as technological or financial constraints, it can disconnect from the main grid and operate independently in island mode.

During grid-connected mode, microgrid sources are controlled to provide constant real and reactive power injection, ensuring stability and reliability of electricity supply within the interconnected grid system.

Microgrids offer versatile operation modes, allowing for both independent off-grid operation and integration with the larger utility grid system. Each mode provides unique benefits and applications, catering to diverse energy requirements and contributing to the resilience and sustainability of energy infrastructure. [5] [6]

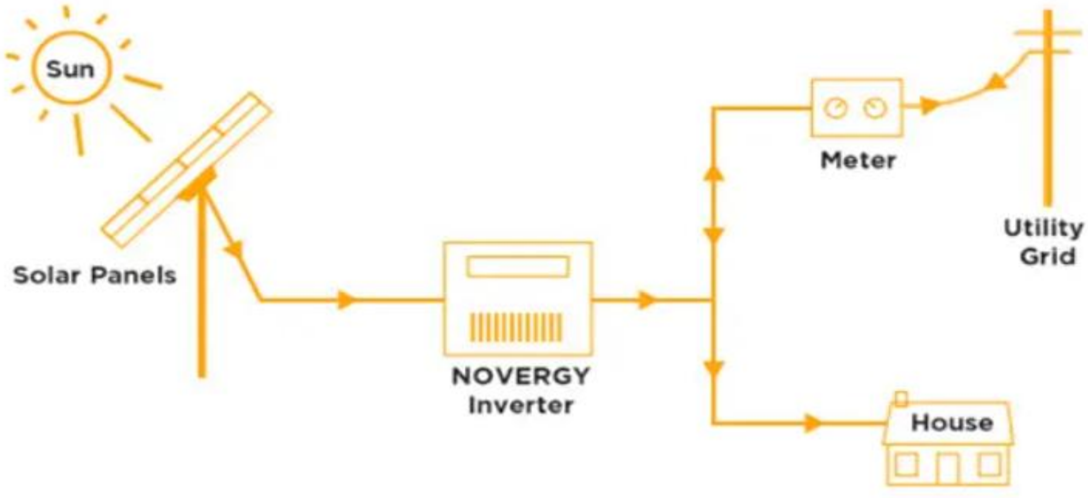

Figure 1.2 Grid-connected architecture

1.6 Microgrid classifications

Microgrids can be categorized based on the type of voltage supplied to the load. Due to their composition of multiple generating sources, including solar, which may provide DC power, while others generate AC power without the need for a converter, microgrids exhibit diverse configurations:

1.6.1 AC Microgrids

AC microgrids utilize AC bus technology to interconnect various energy-producing sources and loads within their network. These microgrids typically comprise distributed generating sources, including renewable energy sources such as solar photovoltaic and wind turbines, alongside conventional power generation sources like engine-powered generators. These generators are dispersed throughout the microgrid and are interconnected via an AC bus system. In AC microgrids, renewable energy sources such as solar panels and wind turbines produce DC output. To integrate this DC output into the microgrid, power electronic-based converters are employed to convert it to AC, ensuring compatibility with the grid.

AC microgrids offer a flexible and scalable solution for integrating renewable energy sources into existing grids. By leveraging AC technology, they facilitate efficient energy distribution and management, enabling seamless integration of diverse generating sources while ensuring reliability and stability of the microgrid system. [7]

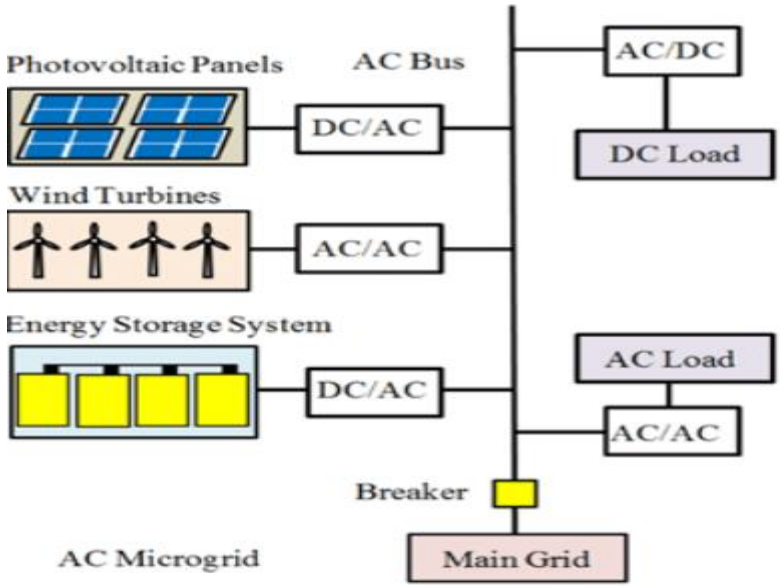

Figure 1.3 AC microgrid architecture

1.6.2 DC Microgrids

DC microgrids operate on a principle similar to AC microgrids but with a distinct difference in their bus network configuration. Unlike AC microgrids, which utilize an AC bus system for interconnection, DC microgrids employ a DC bus network to link distributed generators and loads within the network. The operational voltage of these DC buses typically ranges from 350 to 400 Volts.

In DC microgrids, the main DC bus serves as the central interconnection point and may be branched into additional low-voltage buses to accommodate the requirements of electronics-based loads. Additionally, high voltage gain DC-DC converters play a crucial role in DC microgrids by facilitating the integration of low-voltage power sources such as solar modules, which typically operate at voltages between 20 to 45 Volts. These converters boost the voltage of these sources to match the high voltage DC bus, enhancing the feasibility of their integration into the microgrid system.

DC microgrids offer several advantages, including simplified control and reduced losses associated with DC power transmission. By leveraging a DC infrastructure, these microgrids provide a streamlined approach to integrating renewable energy sources and optimizing energy distribution within the system. [7]

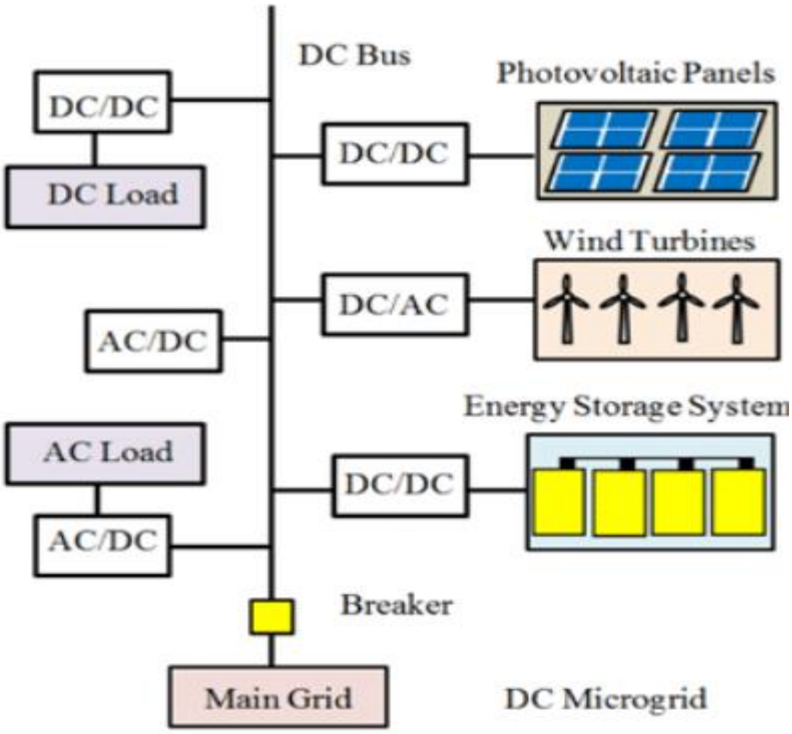

Figure 1.4 DC microgrid architecture

Table 1.1 Comparison between AC & DC microgrids

Factors	**AC Microgrid**	**DC Microgrid**
Conversion efficiency	Multiple energy conversions reduce efficiency	Less conversion processes increases efficiency
Transmission efficiency	Continuous reactive current loss reduces efficiency	Absence of reactive components increases efficiency
Stability	Affected by external disturbances	Free from external effects
Synchronization	Synchronization required	No Synchronization issues
Power supply reliability	Supply can be affected during seamless transfer	Power supply generally reliable
Microgrid controls	Control process complex due to frequency	Simples control approach
Protection system	Simple, cheap and mature protection schemes	Complex, costly and immature protection components
Suitability	AC loads	DC loads
Calculation methods	Complex numbers involves	Only real number used

1.6.3 AC-DC Hybrid Microgrids

In regions lacking reliable access to a robust utility grid, communities, industrial installations, and commercial facilities have historically faced challenges in accessing cost-effective electric power. Often, they have relied on engine- or turbine-driven generator sets, which, while dependable, tend to incur significantly higher operating costs compared to large-scale utility-supplied power.

A more efficient and sustainable approach is now emerging, characterized by the integration of affordable renewable energy sources such as wind or solar power with traditional diesel or gas-powered generation. These hybrid microgrid configurations leverage energy storage solutions to enhance power system reliability and mitigate energy costs.

Hybrid microgrids represent a versatile solution applicable across various settings, including individual buildings, resorts, mine sites, remote villages, and small islands. This adaptability is facilitated by the substantial reduction in the costs of wind and solar energy, as well as the decreased expenses associated with energy storage technologies relative to traditional fuel prices. [7]

The most promising applications of hybrid microgrids are found in scenarios where the total power demand falls within the range of 100 kW to 20 MW. This size range ensures optimal utilization of the hybrid microgrid setup while maximizing cost savings and energy efficiency.

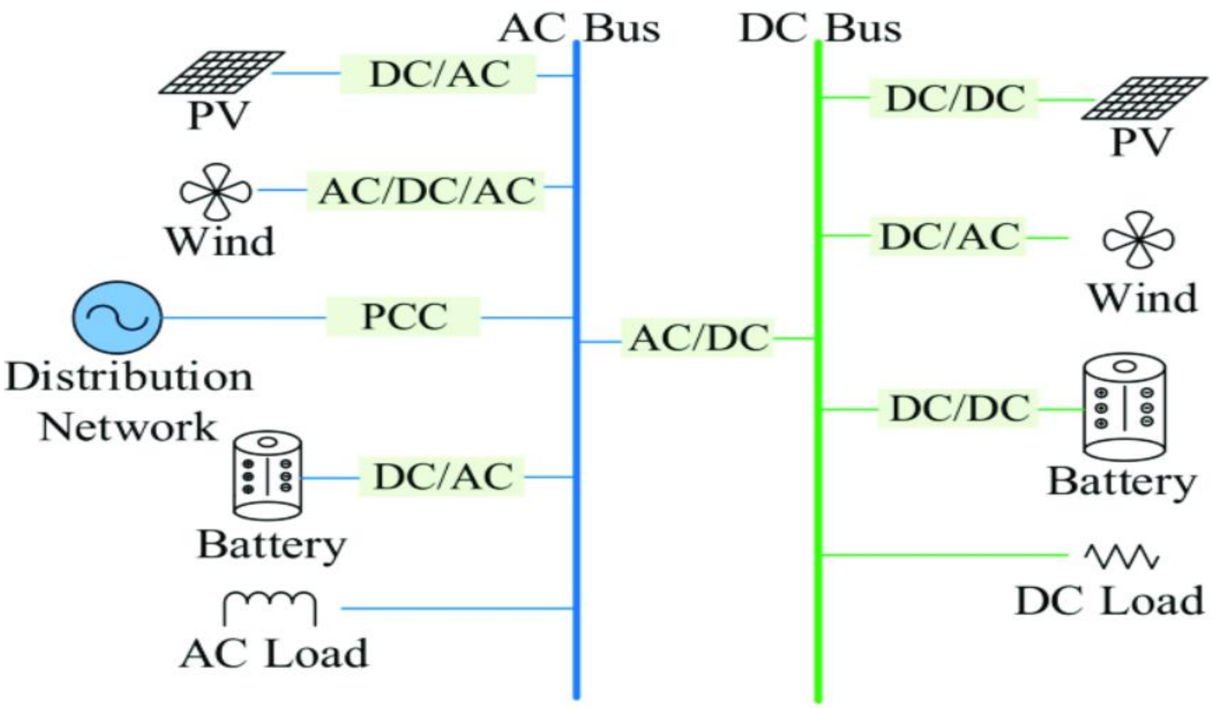

Figure 1.5 Hybrid Microgrid typical structure

1.6.3.1 Advantages of Hybrid Microgrids

- **Improved Power Quality:** Hybrid microgrids offer enhanced power quality by integrating multiple energy sources and storage systems, reducing the likelihood of voltage fluctuations and frequency variations, thus providing a more stable and reliable power supply.
- **Diverse Energy Sources:** The utilization of multiple energy sources, including renewable energy systems and conventional generators, ensures a continuous and reliable power supply, minimizing the risk of outages and enhancing energy security for users.
- **Greenhouse Gas Emissions Reduction:** By incorporating renewable energy sources such as solar and wind power, hybrid microgrids contribute to reducing greenhouse gas emissions, aligning with environmental sustainability goals and mitigating the impacts of climate change.
- **Scalability:** Hybrid microgrids offer scalability, allowing for gradual expansion to meet increasing energy demands over time. This flexibility enables the adaptation of the microgrid system to evolving energy needs and ensures long-term sustainability.

1.6.3.2 Disadvantages of Hybrid Microgrids

- **High Initial Costs:** The installation of multiple technologies, including renewable energy systems, energy storage, and control systems, can be costly, making the implementation of hybrid microgrids financially challenging, particularly for smaller-scale applications.
- **Technological Uncertainty:** The rapid evolution of technology in hybrid microgrids introduces uncertainties regarding the long-term stability and performance of certain components. As newer technologies emerge and existing ones evolve, ensuring compatibility and reliability over the system's lifespan can be a concern.

1.7 Microgrid characteristics

- **Local Energy Generation:** Microgrids are characterized by their localized energy generation, catering to nearby customers. This sets them apart from traditional centralized grids that have dominated electricity provision for decades. Unlike central grids, which transmit electricity over long distances via transmission and distribution lines, microgrids generate power close to their consumers. This proximity minimizes inefficiencies associated with long-distance transmission, where significant portions of electricity—up to 8% to 15%—can dissipate during transit. Microgrid generators are often situated near or within buildings, with solar panels commonly installed on rooftops. [8]

- **Independence and Islanding Capability:** One of the defining features of microgrids is their independence and islanding capability. Microgrids have the capacity to disconnect from the central grid and operate autonomously. This capability proves invaluable during emergencies, such as storms or grid failures, where the central grid experiences outages. The vulnerability of the central grid, with its extensive network of over 5.7 million miles of transmission and distribution lines, increases the risk of widespread outages. For instance, events like the Northeast Blackout of 2003 demonstrated how a single incident, like a tree falling on a power line, can disrupt power supply across multiple states and even international borders. By operating independently, microgrids can mitigate the impact of such disruptions. Although microgrids can function autonomously, they often remain connected to the central grid, fostering a symbiotic relationship. In normal operating conditions, they contribute power to and draw power from the central grid as needed. [8]
- **Intelligent Control and Coordination:** The intelligence of microgrids lies in their sophisticated control systems, particularly the microgrid controller. Serving as the central management unit, the microgrid controller orchestrates various components of the system, including generators, batteries, and building energy systems. It ensures seamless coordination to achieve predefined energy objectives set by consumers. These objectives may encompass priorities such as cost optimization, enhanced electric reliability, promotion of clean energy sources, or other desired outcomes. Through dynamic control mechanisms, the microgrid controller adjusts resource utilization, balancing supply and demand to meet consumer needs efficiently. [8]

1.8 Microgrids components

1.8.1 Energy generation sources

Microgrids are equipped with diverse generation sources that provide electricity, heating, and cooling to users. These sources can be broadly categorized into two main groups: thermal energy sources and renewable generation sources.

1.8.1.1 Conventional Sources

Conventional sources of energy encompass traditional methods of power generation that have been prevalent for many years. These sources include:

- **Diesel Generators:** Diesel generators are commonly utilized in larger applications, such as industrial equipment power supply or backup power provision to critical facilities like hospitals and data centers.
- **Natural Gas Generators:** Natural gas, being a cleaner-burning fuel compared to diesel, is favored for its lower emissions. Natural gas generators are widely deployed in various settings to meet electricity demand efficiently while minimizing environmental impact.

1.8.1.2 Renewable sources

To optimize performance, satisfy energy needs, and mitigate environmental impact, microgrids integrate renewable energy sources. These clean energy sources offer several advantages over conventional technologies, including sustainability and reduced environmental footprint. Examples of renewable energy sources integrated into microgrids include [9]:

Wind Energy: Wind turbines harness kinetic energy from wind to generate electricity, providing a sustainable and reliable power source. [10]

- **Solar Energy:** Solar photovoltaic (PV) panels convert sunlight into electricity, offering a clean and abundant energy source suitable for diverse applications. [11]
- **Geothermal Energy:** Geothermal energy utilizes heat from the Earth's core to generate electricity or provide heating and cooling, offering a renewable and environmentally friendly energy solution. [12]
- **Hydropower:** Hydropower systems harness the energy of flowing water to generate electricity, offering a reliable and renewable energy source with minimal environmental impact. [13]
- **Bioenergy:** Bioenergy encompasses energy derived from organic materials such as biomass, biofuels, and biogas, offering a sustainable and renewable energy source for microgrid applications. [14]

By integrating renewable energy sources into microgrids, these systems can achieve greater sustainability, resilience, and energy independence while reducing reliance on finite fossil fuel resources.

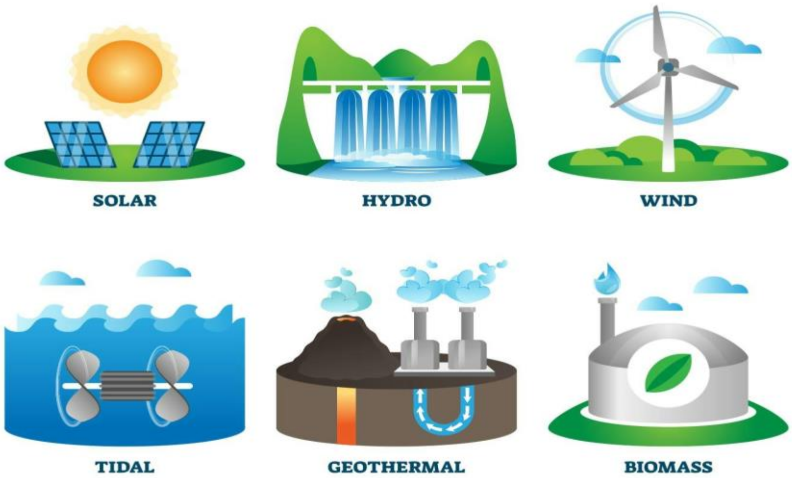

Figure 1.6 Renewable energy resources

1.8.2 Energy storage systems

In a microgrid, energy storage ensures power quality through frequency and voltage regulation, smooths renewable energy output, provides backup power, and aids in cost optimization. It encompasses chemical, electrical, pressure, gravitational, flywheel, and heat storage technologies. Effective management involves coordinating the charging and discharging of storage units based on their capacity to prevent smaller units from discharging too quickly or becoming fully charged before larger ones. [15]

1.8.2.1 Batteries

Batteries store energy chemically during charging and release it electrically during discharge. They are classified into primary (non-rechargeable) and secondary (rechargeable) types, with various materials such as Nickel-Cadmium, Lead-Acid, and Li-ion. Lead-Acid batteries are particularly cost-effective and provide high current capacity for short durations.

1.8.2.2 Super-capacitors

Super-capacitors have a structure of liquid and porous electrodes, creating a high surface area and minimal distance between the electrode and electrolyte, resulting in high capacitance. Energy is stored electrostatically. [15]

1.8.2.3 Flywheels

Flywheels are electromechanical systems storing energy kinetically using a rotating mass. They compensate for combustion engine fluctuations and provide uninterruptible power supply for critical loads. [15]

1.8.3 Power electronics and inverters in microgrid systems

1.8.3.1 AC-DC Converters (Rectifiers)

AC-DC converters, commonly known as rectifiers, serve as essential components in hybrid microgrids. Their primary function is to convert alternating current (AC) power generated by sources such as conventional generators into direct current (DC) power. This DC power is then utilized for storage purposes or to power DC loads within the microgrid system.

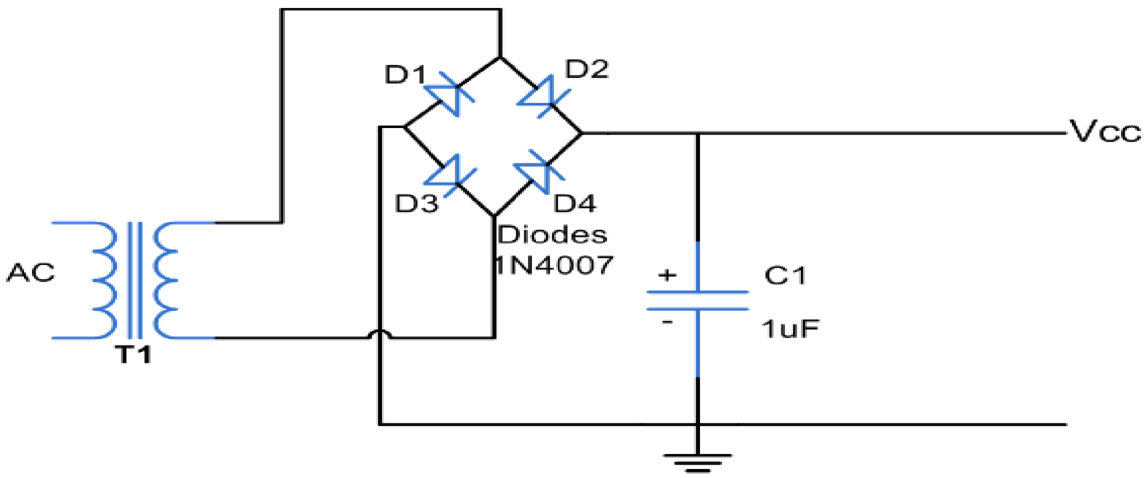

Figure 1.7 Simple AC to DC converter

1.8.3.2 DC-AC Converters (Inverters)

Inverters are indispensable for converting DC power obtained from energy storage systems, such as batteries, and photovoltaic (PV) systems into alternating current (AC) power. This AC power is crucial for distribution to AC loads within the microgrid or for feeding surplus power into the main grid.

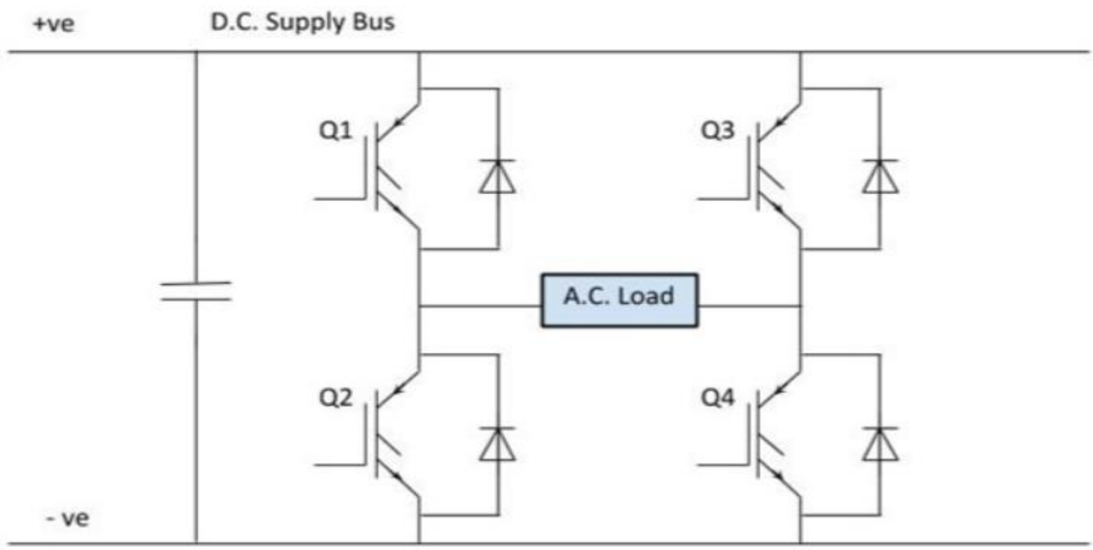

Figure 1.8 DC-AC Converter design

1.8.3.3 Bidirectional AC to DC Converters

A significant advancement in power electronic converters is the bidirectional AC to DC converter. This versatile converter topology, illustrated in Figure 1.14 (if included), comprises six Insulated Gate Bipolar Transistors (IGBTs) connected to a three-phase power source. Its unique design allows it to function both as a rectifier and an inverter simultaneously. By integrating a DC capacitor, this converter ensures a stable output voltage. It plays a vital role in efficiently managing power flow between the AC bus and the DC bus of the microgrid system.

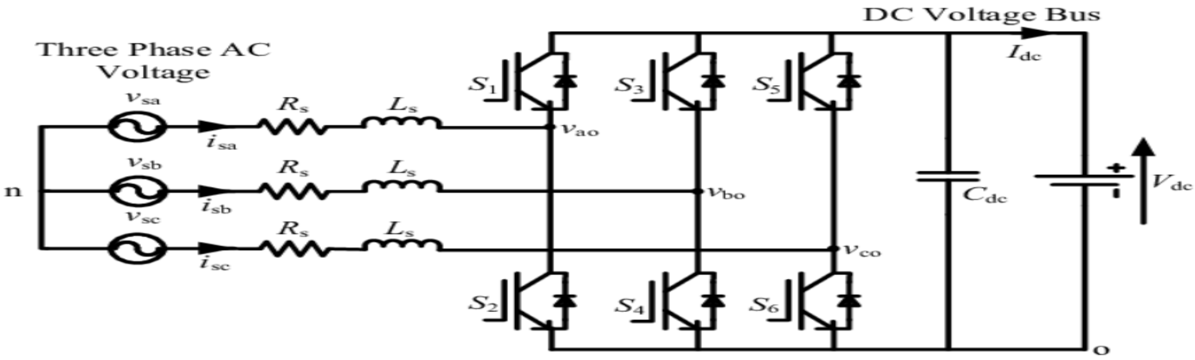

Figure 1.9 Three-phase bidirectional AC-DC converter topology

1.8.3.4 DC to DC Converters

DC to DC converters are crucial for matching voltage levels between various components within the microgrid. For instance, they are utilized to harmonize the voltage output of solar panels or batteries with the requirements of loads or other storage systems.

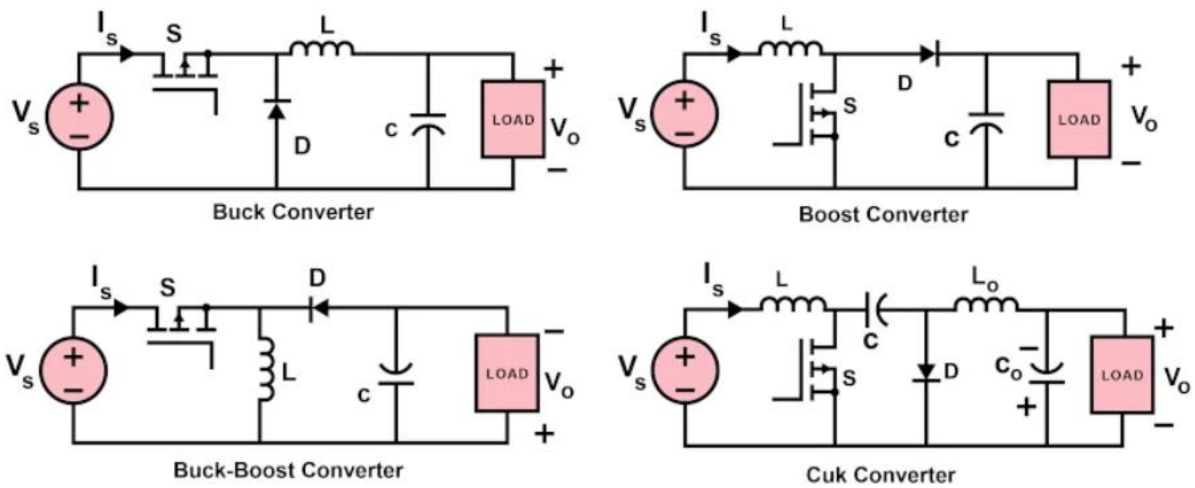

Figure 1.10 Basic DC-DC converter circuit diagrams.

1.8.3.5 Bidirectional DC to DC Converters

Another significant advancement in power electronics is the bidirectional DC to DC converter. This device enables bi-directional conversion of DC voltage from one level to another. It plays a pivotal role in connecting energy storage systems, such as batteries, and PV systems to the DC bus of the microgrid.

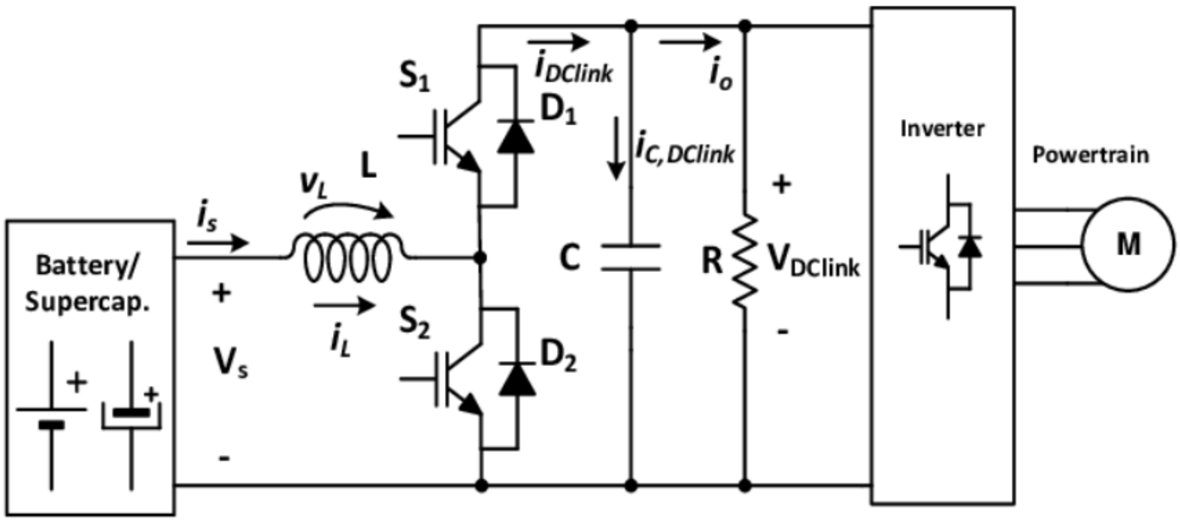

Figure 1.11 Schematic of the bidirectional DC-DC converter.

1.8.4 Loads

In a microgrid (MG), electrical loads are typically categorized into two main groups: critical loads and non-critical loads. The distinction between these categories is crucial for ensuring reliable and efficient operation of the microgrid system. [16]

- **Critical Loads:** Critical loads are those that require a consistently high level of reliability and uptime. These loads are essential for maintaining the functionality and safety of critical infrastructure, such as hospitals, emergency response centers, and certain industrial processes. Ensuring uninterrupted power supply to critical loads is paramount, as any disruption could have severe consequences. Therefore, the microgrid system must prioritize the provision of energy to critical loads, even during emergencies or grid disturbances.

- **Non-Critical Loads:** Non-critical loads, on the other hand, are those that are less essential for immediate operation and can tolerate occasional interruptions or shedding during emergency situations. Examples of non-critical loads include lighting, HVAC systems in non-essential buildings, and certain appliances in residential settings. During periods of high demand or limited supply, non-critical loads may be intentionally shed or temporarily shifted to different times of the day to maintain system balance and ensure the reliable operation of critical loads.

The management of simultaneous generation, storage, and demand within the microgrid presents a complex energy management problem. This challenge requires sophisticated control and optimization algorithms to dynamically balance supply and demand while maximizing operational flexibility and efficiency. By effectively coordinating generation, storage, and demand-side management strategies, the microgrid can adapt to changing conditions in real-time, optimize energy utilization, and enhance overall system performance.

1.9 Conclusion

In conclusion, microgrids emerge as the future of electric power generation, particularly in rural areas, offering a sustainable and environmentally friendly solution. With a strong reliance on renewable energy resources, such as solar and wind, microgrids contribute to a greener energy landscape by reducing dependence on fossil fuels and lowering carbon emissions. This shift towards renewable energy sources not only promotes environmental conservation but also fosters energy independence.

By integrating renewable energy sources into microgrid systems, we pave the way for greater efficiency in power production. Despite their limitations, microgrids offer significant advantages that can be optimized to overcome challenges and enhance overall performance. Through continuous innovation and investment in renewable energy technologies, microgrids hold immense potential to revolutionize energy distribution and contribute to a more sustainable future.

In essence, microgrids represent a pivotal step towards achieving a cleaner, more resilient, and self-sufficient energy ecosystem. By harnessing the power of renewable resources, we can pave the way for a brighter and more sustainable energy future for generations to come.

CHAPTER 2: *PHOTOVOLTAIC SYSTEMS*

2.1 Introduction

Daryl Chapin, Calvin Fuller, and Gerald Pearson, Bell Labs researchers, produced the first viable solar cell in 1954. Using silicon wafers, the cell's efficiency was significantly higher than Charles Fritts' selenium cell, at approximately 6%, surpassing anything previously accomplished. Bell Labs exhibited the technique for the first time, powering a small miniature Ferris wheel and a solar-powered radio transmitter.

Following these discoveries, some of the first solar panels were deployed in orbit to power satellites. In 1958, the radios aboard the Vanguard I satellite were powered by a modest one-watt panel. Other satellites, such the Vanguard II, Explorer III, and Sputnik-3 followed, and solar energy is still widely employed today in space.

Solar power technology has undergone constant development over the years, resulting in lower costs and more efficiency, which has allowed solar panels to become widely available. The University of South Wales researchers achieved 34.5% efficiency in 2016. In the same year, Bertrand Piccard piloted the Solar Impulse 2, the most potent solar-powered aircraft ever, to make the first circumnavigation of the globe with no greenhouse gas emissions. [17]

2.2 Stability of power grid systems and the role of renewable energy

The stability of a power grid system is crucial for maintaining a reliable supply of electricity. Stability refers to the grid's ability to maintain continuous operation and to return to normal conditions after a disturbance, such as sudden changes in load demand or unexpected outages of power plants. A stable power grid ensures that electricity is consistently available to consumers without interruptions.

One of the significant challenges to grid stability is the loss of synchronism. Synchronism refers to the coordinated operation of different power generators within the grid. When generators fall out of sync due to imbalances between supply and demand or other technical issues, it can lead to a cascade of failures across the grid. This loss of synchronism can result in widespread blackouts, where large areas are left without power. Blackouts not only disrupt daily life but can also have severe economic and safety implications.

A primary factor contributing to instability and potential blackouts is the insufficiency of power plants to meet load demand at all times. Traditional power plants, such as those burning fossil fuels, may not always be able to ramp up production quickly enough to match sudden increases in demand or may experience outages that reduce their capacity. This inadequacy underscores the need for a more flexible and resilient energy system.

To address these challenges, the integration of renewable energy sources into the power grid has emerged as a vital solution. Renewable energies, such as wind, hydro, and solar power, offer several benefits that enhance grid stability and reduce the risk of blackouts. They provide a diverse energy mix that can supplement traditional power generation, reducing the strain on individual power plants and increasing the overall resilience of the grid.

In our project report, we focus on solar energy as a key renewable resource for enhancing grid stability. Algeria, with its high levels of solar irradiation, is particularly well-suited for solar energy projects. The country receives abundant sunlight throughout the year, making it an ideal location for solar power generation. By harnessing this plentiful solar resource, Algeria can significantly increase its power generation capacity, helping to meet peak load demands more effectively and reducing the likelihood of power shortages.

Solar energy not only contributes to a more stable and reliable power grid but also offers environmental benefits by reducing greenhouse gas emissions and reliance on fossil fuels. As solar technology continues to advance and become more cost-effective, its integration into the power grid will play a crucial role in achieving energy security and sustainability.

2.3 Global horizontal irradiation in Algeria

Global horizontal irradiation (GHI) is a measure of solar energy received per unit area by a horizontal surface. It is a crucial metric for assessing the potential for solar energy production. Algeria, with its vast desert regions and sunny climate, has significant potential for harnessing solar energy. [18]

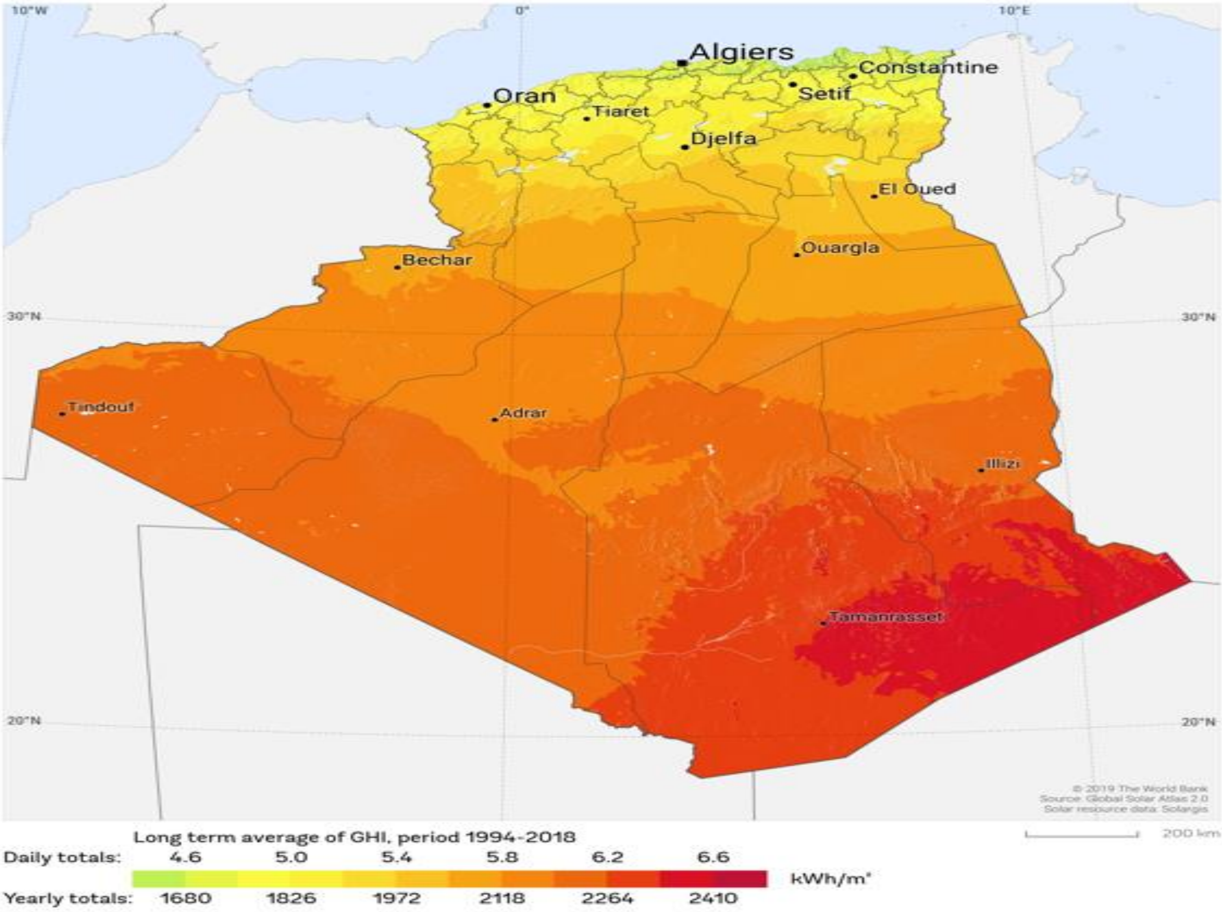

Figure 2.1 Global horizontal irradiation map in Algeria

Algeria experiences some of the highest levels of solar irradiation in the world. The country is situated in the Sun Belt, which is characterized by high solar radiation levels.

According to solargis report, the average GHI in Algeria ranges from approximately 4.6 to 6.6 kWh/m²/day. In the northern coastal regions, GHI values are typically lower, ranging from 4.6 to 5.4 kWh/m²/day, Where the central and southern regions, particularly the Sahara Desert, experience higher GHI levels, often exceeding 6 kWh/m²/day and reaching up to 6.6 kWh/m²/day in some areas.

2.4 PV effect

The photovoltaic effect occurs in solar cells. These solar cells are made up of two different types of semiconductors: p-type and n-type, which are connected together to form a p-n junction. When these two types of semiconductors are combined, an electric field forms in the junction region as electrons migrate to the positive p-side and holes to the negative n-side. This field causes negatively charged particles to travel in one direction while positively charged particles move in the opposite direction.

Light is made up of photons, which are basically microscopic bundles of electromagnetic radiation or energy. These photons can be absorbed by a photovoltaic cell, the sort of cell used in solar panels. When light with a proper wavelength strikes these cells, energy from the photon is transmitted to an atom of the semiconducting material in the p-n junction. Specifically, energy is transmitted to the material's electrons. This leads the electrons to move into a higher energy state known as the conduction band. This leaves a "hole" in the valence band from which the electron hopped up. The movement of the electron caused by extra energy produces two charge carriers, an electron-hole pair.

When unexcited, electrons hold the semiconducting material together by creating connections with neighboring atoms, preventing them from moving. However, in their excited condition in the conduction band, these electrons can freely flow through the material. The electric field created by the p-n junction causes electrons and holes to travel in the opposite direction, as expected. Instead of being drawn to the p-side, the liberated electron tends to gravitate toward the n-side. The motion of the electron generates an electric current in the cell. When an electron moves, it leaves behind a "hole". This hole can also move, but in the opposite direction from the p-side. This mechanism generates a current in the cell. A diagram of this process can be seen in the figure bellow. [19]

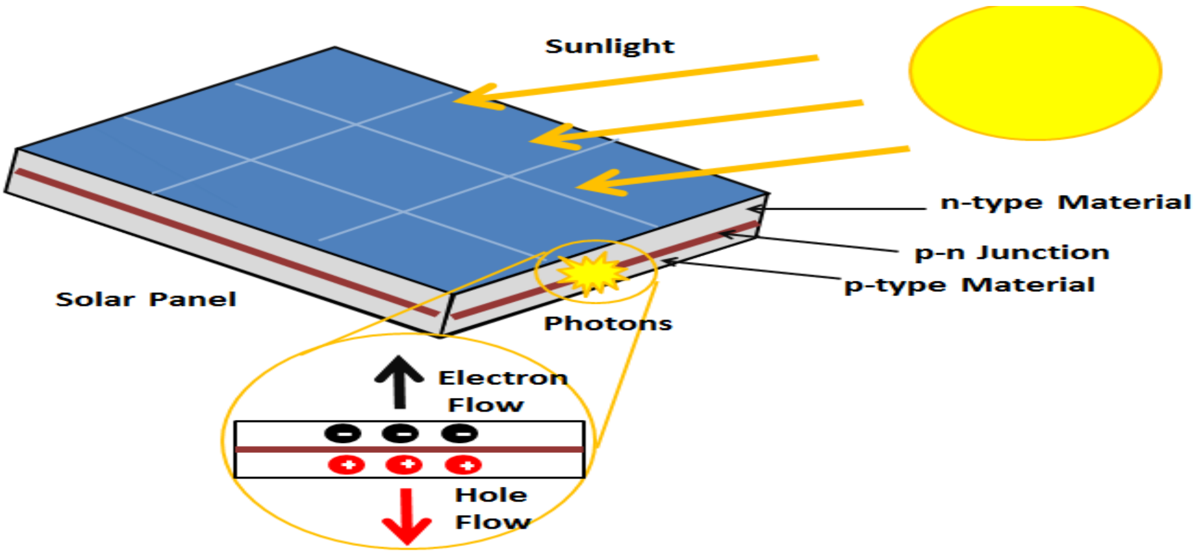

Figure 2.2 A diagram showing the photovoltaic effect.

2.5 Pv cell

A photovoltaic cell is composed of semiconductor material. When photons strike a PV cell, they can either reflect off it, pass through it, or be absorbed by the semiconductor material. Only absorbed photons offer energy for electricity generation. When a semiconductor material absorbs enough sunshine (solar energy), electrons are released from its atoms. Special treatment of the material surface during manufacture makes the front surface of the cell more responsive to dislodged, or free, electrons, allowing electrons to spontaneously migrate to the cell's surface.

2.5.1 The flow of electricity in a solar cell

There is an imbalance in electrical charge between the front and rear surfaces of the solar photovoltaic cell due to the migration of electrons, which are all negatively charged, toward the front surface. A voltage potential similar to that of a battery's positive and negative terminals is therefore produced by this imbalance. The electrons are taken up by the cell's electrical conductors. Electricity flows through an electrical circuit when its conductors are linked to an external load, like a battery.

Solar cells generate a voltage of 0.5-0.7 V and a current density of a few tens of mA/cm2, depending on solar radiation strength and spectrum [20].

2.5.2 Equivalent circuit for photovoltaic cell

Figure 2.3 shows the equivalent circuit of a PV cell. The current source Iph represents the cell's photocurrent. Rsh and Rs are the cell's intrinsic and series resistances, respectively. Typically, the value of Rsh is quite big and that of Rs is very small, thus they can be ignored to simplify the analysis. [20]

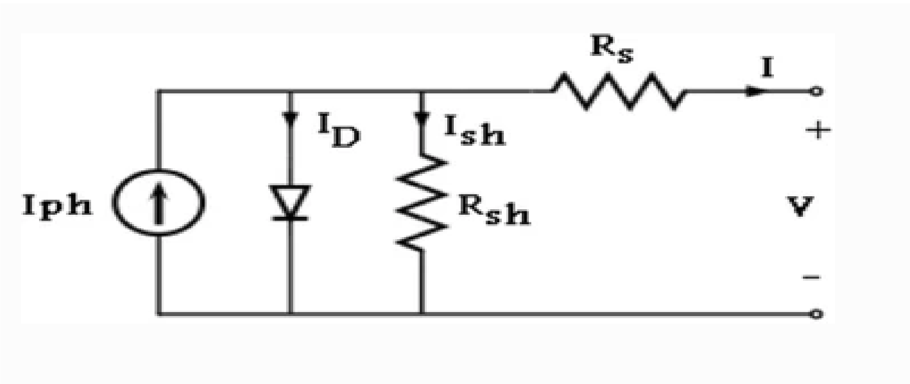

Figure 2.3 PV cell equivalent circuit

2.5.3 Solar cell model

The voltage-current characteristic equation of a solar cell is given as:

$$I = I_{PH} - I_S \exp[\, q(V + IR_S)/ kT_C A) - 1] - (V + I_{RS})/ R_{SH} \quad (2.1)$$

Where I_{PH} is a light-generated current or photocurrent, I_S is the cell saturation of dark current, **q(1.6×10^{-19}C)** is an electron charge, **k (1.38× 10^{-23} J/K)** is a Boltzmann's constant, T_C is the cell's working temperature, A is an ideal factor, RSH is a shunt resistance, and RS is a series resistance. The photocurrent mainly depends on the solar insolation and cell's working temperature, which is described as

$$I_{PH} = [I_{SC} + K_I\,(T_C - T_{Ref})]\,\lambda \tag{2.2}$$

Where I_{SC} is the cell's short-circuit current at a 25°C and 1kW/m^2 , K_I is the cell's short-circuit current temperature coefficient, T_{Ref} is the cell's reference temperature, and λ is the solar insolation in kW/m2 . On the other hand, the cell's saturation current varies with the cell temperature, which is described as

$$I_S=I_{RS}(T_C/T_{Ref})^3\,exp[qE_G(1/T_{Ref}-1/T_C)/kA] \tag{2.3}$$

Where I_{RS} is the cell's reverse saturation current at a reference temperature and a solar radiation, E_G is the bang-gap energy of the semiconductor used in the cell. The ideal factor A is dependent on PV technology and is listed in Table 2.1. [21]

Table 2.1 Factor A dependence on PV technology

Technology	**A**
Si-mono	1.2
Si-poly	1.3
a-Si:H	1..8
a-Si:H tandem	3.3
a-Si:H triple	5
CdTe	1.5
CIS	1.5
AsGa	1.3

2.6 Solar module and array model

PV cells typically produce less than 2W at 0.5V, hence a series-parallel arrangement on a module is necessary to provide sufficient power. A PV array consists of many PV modules coupled in series and parallel circuits to create necessary current and voltage. **Figure2.4(a)** illustrates the comparable circuit for a solar panel organized in N_P parallel and N_S series.

The terminal equation for the current and voltage of the array becomes as follows:

$$I = N_P.I_{ph} - N_P.I_S[exp(q(V/N_S + IR_S/N_P)/kT_CA)-1]-(Np.V/N_S + IR_S)/R_{SH} \tag{2.4}$$

PV efficiency is responsive to slight changes in R_S but not to variations in R_{SH}. In a PV module or array, the series resistance is significant, but the shunt down resistance approaches infinity, assuming an open circuit. PV cells are often linked in series to form a PV module for optimal operating voltage in commercial PV products. PV modules are stacked in a series-parallel arrangement to provide the necessary power output.

An appropriate equivalent circuit for all PV cell, module, and array is generalized and expressed in **Figure 2.4(b)**

It can be shown that $\mathbf{N_S = N_P = 1}$ for a PV cell, $N_P = 1$ and: N_S series number of cells for a PV module, and N_S and N_P: series-parallel number for a PV array. The mathematical equation of generalized model can be described as

$$I = N_P I_{PH} - N_P I_S [exp(q(V/N_S + IR_S/N_P)/ kT_C A)-1] \quad (2.5)$$

The most simplified model of generalized PV module is depicted in **Figure 2.4(c).** The equivalent circuit is described on the following equation

$$I = N_P I_{PH} - N_P I_S [exp(qV/N_S kT_C A)-1] \quad (2.6)$$

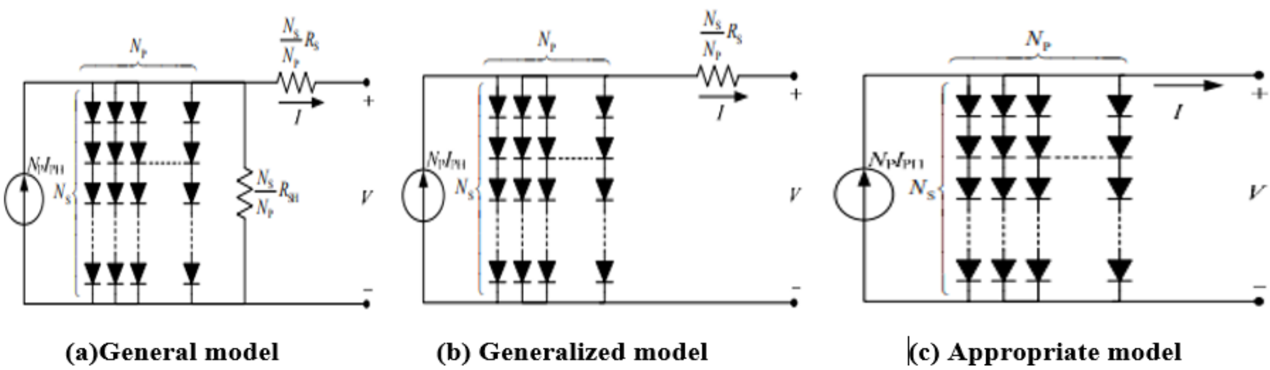

Figure 2.4 Equivalent circuit models of generalized PV.

2.6.1 Determination of model parameters

The specs of pv products may be examined to identify all of the model parameters. The open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) are the two most significant metrics that are frequently used to describe the electrical performance of the cell. Given the implicit and nonlinear nature of the aforementioned equations, it is challenging to find an analytical solution for a given set of model parameters at a given temperature and irradiance. Since normally $I_{ph} >> I_S$ and ignoring the small diode and ground-leakage currents under zero-terminal voltage, the short-circuit current I_{SC} is approximately equal to the photocurrent I_{ph}, i.e., $I_{ph}=I_{SC}$

On the other hand, the V_{OC} parameter is obtained by assuming the output current is zero. Given the PV open-circuit voltage V_{OC} at reference temperature and ignoring the shunt-leakage current, the reverse saturation current at reference temperature can be approximately obtained as:

$$I_{RS} = I_{SC} /[\exp(qV_{OC}/N_S kAT_C)-1] \quad (2.7)$$

In addition, the maximum power can be expressed as

$$P_{max}= V_{max}\, I_{max}= \gamma V_{OC}\, I_{SC} \quad (2.8)$$

Where V_{max} and I_{max} are terminal voltage and output current of PV module at maximum power point (MPP), and γ is the cell fill factor which is a measure of cell quality. [22]

2.7 Solar cell I –V characteristics

Solar cell I-V characteristics: Curves are a graphical depiction of a solar cell or module's operation, summarizing the relationship between current and voltage under the given irradiance and temperature circumstances. I-V curves present the necessary information for configuring a solar system to function as near to its ideal peak power point (MPP) as possible. [23]

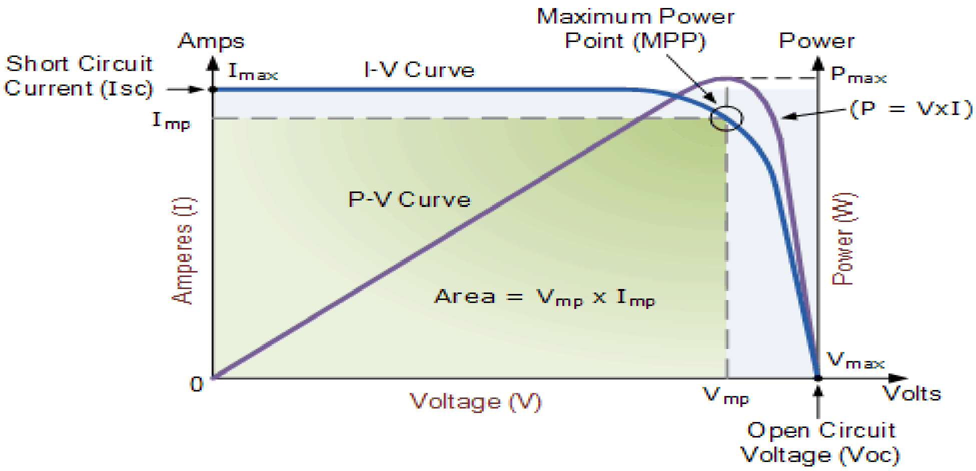

Figure 2.5 Solar Cell I-V Characteristic Curve

The current-voltage (I-V) characteristics of a typical silicon photovoltaic cell operating under normal conditions are displayed in the above graph. A single solar cell's or panel's power output is calculated by multiplying its output voltage by its current (I x V). The power curve above is achieved for a given radiation level if the multiplication is performed, point for point, for all voltages from short-circuit to open-circuit conditions.

The voltage across the solar cell is at its greatest when it is open-circuited, or disconnected from any load, and the current is at its lowest (zero). This is referred to as the solar cells open circuit voltage, or Voc. On the other hand, when the positive and negative leads of the solar cell are shorted out, or when the cell is short circuited, the voltage across the cell is at its lowest point—zero—but the current coming out of the cell reaches its maximum—this is known as the solar cell's short circuit current, or **Isc.**

Of course, neither of these two conditions generates any electrical power, but there must be a point somewhere in between were the solar cell generates maximum power.

Nonetheless, the power achieves its maximum value at Imp and Vmp for a certain combination of current and voltage. Stated differently, the top right corner of the green rectangle represents the instant at which the cell produces its highest amount of electrical power. This is the MPP, or maximum power point. As a result, a photovoltaic cell's (or panel's) optimal performance is determined by its maximum power point.

A solar cell's maximum power point (MPP) is located close to the curve's bend in the I-V characteristics. The open circuit voltage and short circuit current may be used to determine the corresponding values of Vmp and Imp, which are: Vmp ≅ (0.8–0.90)Voc and Imp ≅ (0.85–0.95)Isc. The actual output power will fluctuate in response to variations in the surrounding temperature since the voltage and current of solar cells are temperature-dependent.

2.7.1 Solar panel I-V characteristic curves

A photovoltaic array is made up of smaller PV panels interconnected together. Then the I-V curve of a PV array is just a scaled up version of the single solar cell I-V characteristic curve as shown. [24]

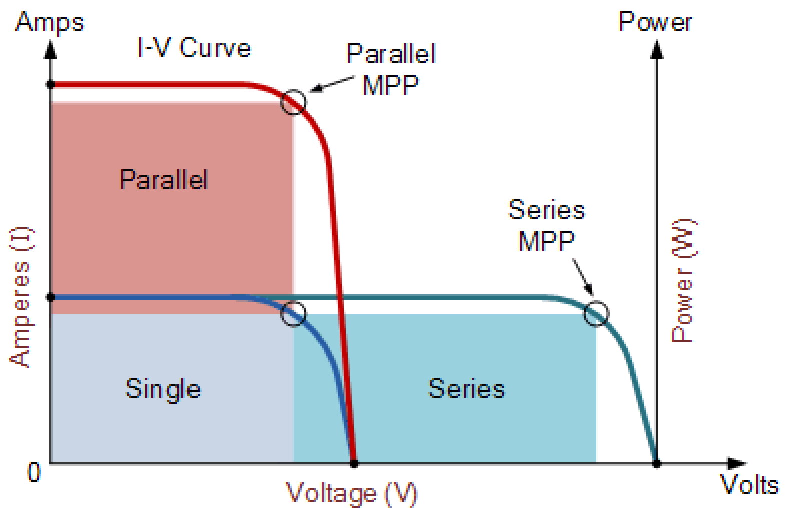

Figure 2.6 Solar Panel I-V Characteristic Curves

Photovoltaic panels can be linked or connected in series, parallel, or both to improve the voltage or current capacity of a solar array. If the array panels are joined in series, the voltage increases; if they are connected in parallel, the current increases.

The electrical power in Watts generated by these various photovoltaic combinations will remain the product of voltage and current (P = V x I). Regardless of how the solar panels are linked, the top right corner will always represent the array's maximum power point (MPP).

2.8 Solar array parameters

- **V_{OC}** = open-circuit voltage - This is the array's maximum voltage when the terminals are not connected to a load. This value is significantly greater than Vmp, which refers to the functioning of the PV array, which is determined by the load. Voc is dependent on the number of PV panels linked in series.
- **I_{SC}**, or short-circuit current, is the highest current that the photovoltaic array can produce in a short circuit condition, which occurs when the output connections are shorted together. Compared to Imp, which represents the typical working circuit current, this number is substantially larger.
- **Maximum power point**, or MPP for short, is the point at which the power provided by the array linked to the load (batteries, inverters) reaches its maximum value. MPP is calculated as follows: Imp x Vmp. A solar array's greatest power point is expressed in Watts (W) or peak Watts (Wp).
- **FF** = fill factor - The fill factor is the product of the open-circuit voltage and the short-circuit current (VOC x ISC), which represents the maximum power that the array can really supply under typical operating circumstances. An indication of the array's quality may be found in its fill factor value; the closer the fill factor is to unity, or 1, the more power the array can produce. Values typically range from 0.7 to 0.8.
- **%eff** = percent efficiency: The ratio of a photovoltaic array's maximum power output to the amount of solar radiation that strikes the array determines the array's efficiency. Generally speaking, a solar array's efficiency ranges from 10 to 12 percent, depending on the kind of photovoltaic cell being used—monocrystalline, polycrystalline, amorphous, or thin film [25].

2.9 Types of solar photovoltaic cells

2.9.1 Monocrystalline silicon solar panels

Because monocrystalline silicon has a 15% efficiency, it is the most efficient type of solar PV cell but also the costliest. Just by virtue of their higher energy output—they can generate up to four times the power of thin-film solar panels—they take up less space than other cells. They function better in low light and have a longer lifespan than other panels. The primary drawback is the expense, which frequently results in homeowners choosing another option instead of this one. Additionally, it may be affected by shadows or dirt, which can short circuit the circuit, and the fact that the cells must be sliced into wafers during manufacture makes it seem like a wasteful procedure.

Figure 2.7 Monocrystalline silicon solar panel

2.9.2 Polycrystalline solar panels

Which have an efficiency of 13%, are frequently seen as a more cost-effective option, especially for homeowners. They are formed by melting together many smaller silicon crystals, which are then recrystallized. Compared to monocrystalline panels, the method of creating them is less complicated and wasteful. While they may not last as long as their more expensive version, they do suffer more in extreme temperatures. Due to its lower energy conversion efficiency, polycrystalline solar panels have one major drawback: you need more of them.

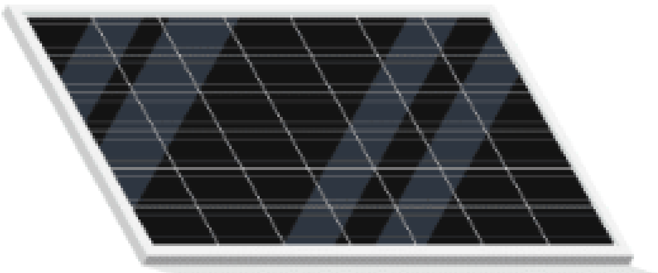

Figure 2.8 Polycrystalline solar panel

2.9.3 Amorphous/thin film solar panels

At 7%, thin film solar panels are among the least efficient on the market but they are the cheapest option. They are composed of non-crystalline silicone that may be applied in a thin layer to another material, such glass, and they function effectively in low light, including moonlight. The primary benefit is that it can be mass manufactured at a far lower cost; yet, it works better in scenarios where space is not a major concern. The primary drawbacks of thin-film solar panels are that they break down more quickly than crystalline cells and are rarely employed for residential usage [26].

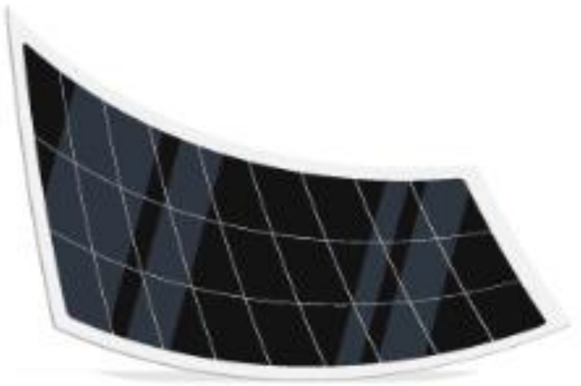

Figure 2.9 Thin film solar panel

2.10 Solar panel degradation rate

The effectiveness of solar panels gradually decreases as they are exposed to sunshine and weather. The speed at which solar panels lose output and efficiency over time is known as their degradation rate. Usually, a percentage of the yearly power production loss is used to quantify this.

The effectiveness of solar panels naturally decreases with exposure to sunshine, temperature changes, humidity, mechanical stress, and manufacturing quality. Most solar panels have an annual deterioration rate of around 0.5% on average. Due to this slow decline in power output, a solar panel's efficiency after 25 years should normally be around 87.5% of its initial capacity.[26] [27]

2.11 Conclusion

Photovoltaic systems are a cornerstone of the global transition to renewable energy. Their ability to provide clean, sustainable, and increasingly cost-effective electricity makes them a vital component of modern energy strategies. As technology continues to evolve and costs decline, the adoption of PV systems is expected to accelerate, contributing to a more sustainable and resilient energy future. Embracing PV technology not only addresses environmental concerns but also offers economic and social benefits, paving the way for a cleaner, more sustainable world.

CHAPTER 3: *SIMULATION AND RESULTS*

3.1 Introduction

As previously discussed, the integration of multiple energy sources has become essential to meet varying load demand scenarios and enhance the stability of micro-grid systems. This chapter focuses on the modeling and simulation of a hybrid power system under different conditions, including variable load, solar irradiation, and a synchronous generator as the primary power source.

The modeling and simulation of the entire system have been employed using the Matlab/Simulink environment. This comprehensive simulation enables us to analyze and evaluate the performance of the micro-grid under different operating conditions.

The main components of our module under investigation include a synchronous generator, which acts as the base power generator, a solar panel for harnessing renewable energy, and a battery for efficient energy storage. The synchronous generator ensures a reliable and stable power supply, while the solar panel contributes renewable energy to the system. The battery serves as a storage unit, capturing and storing excess power generated by the photovoltaic (PV) system.

By integrating these components, our aim is to optimize power generation and storage, ensuring a reliable and sustainable energy supply. The synchronous generator provides a stable power source, while the solar panel harnesses renewable energy from sunlight. The battery acts as a storage unit, enabling the storage of surplus power generated by the PV system for future use.

3.2 Key components

3.2.1 Power grid model

The SIMULINK power system model consists of of Power plant with an initial output of 66 kV, Three-phase Transformer to decrease the voltage from 66 kV to 6.6 kV, three-phase transmission line and Pole Mounted Transformer further reduces the voltage from 6.6 kV to 200 V.

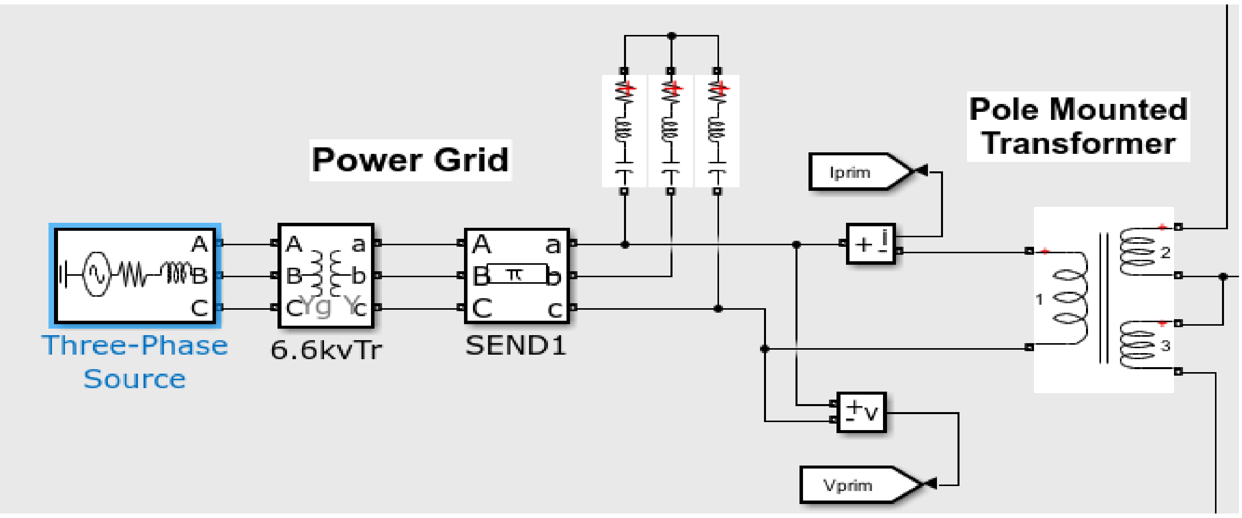

Figure 3.1 MATLAB/SIMULINK model of the power grid

3.2.2 Battery modeling

The Battery model plays a crucial role in the micro-grid system by ensuring a stable and reliable power supply. During periods of high power demand, it supplies additional power when the micro-grid's power is insufficient to meet the demand. This ensures a consistent and reliable power supply during high-demand periods.

On the other hand, from 12h to 18h, when power demand tends to decrease and the irradiance is at its peak, the battery model switches to absorption mode. During this time, the battery absorbs surplus power generated by the PV system. This helps maintain a balanced power flow and prevents excess energy from going to waste.

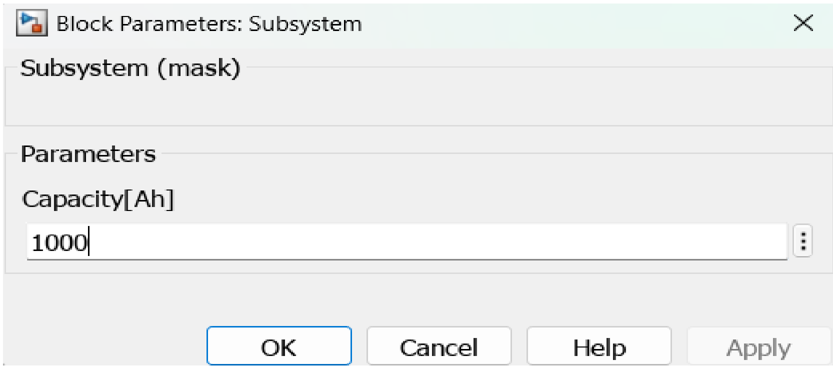

Figure 3.2 Battery profile

In addition, we have to make sure to protect our energy storage system to ensure a maximum life cycle. To achieve this, we need to carefully determine the appropriate timings for utilizing stored energy or storing any excess power generated by the PV system. By doing so, we can effectively prevent the storage system from overcharging (above 0.9) or discharging excessively (below 0.2).

3.2.3 Pv system modeling

In a photovoltaic (PV) system, the amount of energy produced is influenced by the irradiance, which represents the amount of sunlight or solar radiation that reaches the PV array. The output current of a solar cell within the PV array is directly proportional to the amount of light (irradiance) that strikes it. Additionally, the temperature also affects the performance of the solar cells and hence the output factors.

PV systems have numerous advantages over other renewable energy sources (RES). One significant advantage is their simplified installation process compared to other RES technologies, which often require complex power switching converters for micro-grid connection. The efficiency of a PV cell is directly influenced by the number of integrated solar cells. By increasing the quantity of solar cells, a PV system can improve its overall efficiency and generate more electricity from available sunlight. This scalability enhances the versatility and adaptability of PV systems, allowing them to meet varying energy demands effectively.

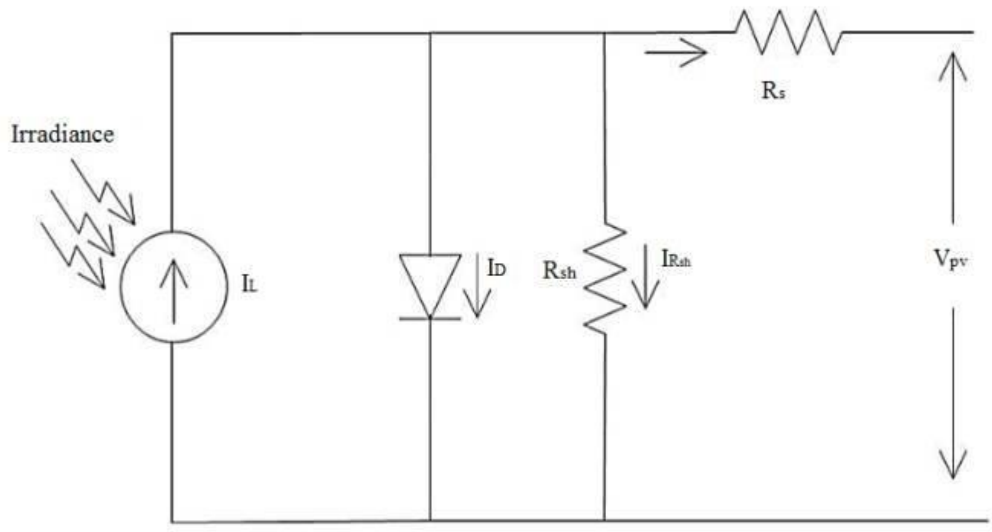

Figure 3.3 The equivalent circuit of the solar cell

A PV cell can be represented by a current source connected in parallel with a diode, since it generates current when it is illuminated and acts as a diode when it is not. The equivalent circuit model also includes a shunt and series internal resistance that can be represented by resistors Rs and Rsh.

The current that passes through these components is controlled by the voltage (V) across them.

$$V = V_{PV} + I_{PV} . R_S \tag{3.1}$$

The physical structure of a solar cell is similar to that of a diode in which the p–n junction is subjected to sun exposure. The basic semi-conductor theory is captured in the following equations:

$$\mathbf{I} = Iph,ll - ID \tag{3.2}$$

$$ID = Io,ll * exp\,[(qVKTc) - 1] \tag{3.3}$$

The above eqs can be modified to obtain the current–voltage characteristics of a photovoltaic cell employed in the solar panel by adding some parameters as given in Equation:

$$I = Iph - Io * exp\,[((V+Ipv*Rs)Vt) - 1] - [V+Ipv*RsRsh] \tag{3.4}$$

Where:

Io,cell : The saturated reverse current or leakage current, A.

Iph,cell: The Photocurrent, is the current produced by the incident light and function of irradiation level and junction temperature, A.

Rs : Series resistance , Ω

Rsh: Shunt resistance, Ω

Vt: Thermal voltage, V.

α: Ideality factor [1.6 for silicon].

V: the voltage across PV cell.

I: is the output

I_PV: is the current across PV cell

ID : The diode current modeled by the equation for a Shockley diode, A.

3.2.4 Load modeling

Electricity demand varies throughout different periods based on consumer consumption, with some periods experiencing an increase in demand while others see a decrease. To simulate a realistic load demand, a variable load is employed, representing three houses with a primary energy consumption of 2 KW each.

The controlled current source allows for precise adjustment of the load's power demand by injecting a pre-constructed signal. Conversely, the snubber resistance plays a crucial role in minimizing power dissipation during both increasing and decreasing load conditions. It serves to prevent false turn-on and turn-off of the current source caused by overvoltage, while also limiting the rate of change in voltage and current. By effectively managing these aspects, the snubber resistance ensures stable operation and safeguards against unwanted power fluctuations.

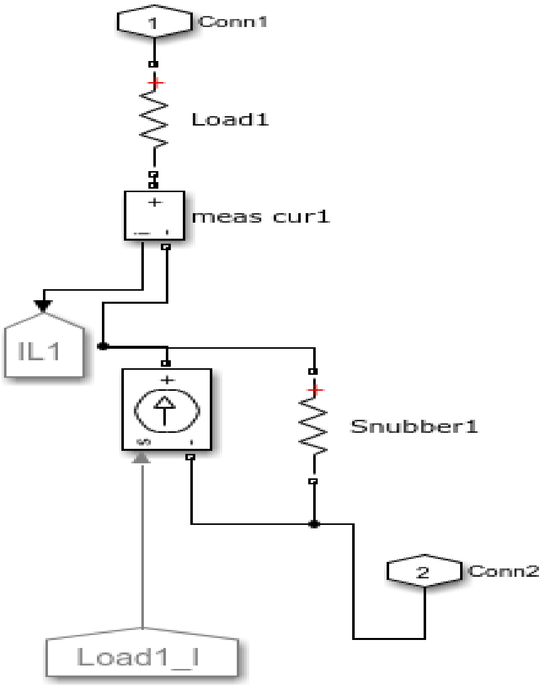

Figure 3.4 Load model

3.3 Simulation results and discussion

3.3.1 Power grid supplying variable load

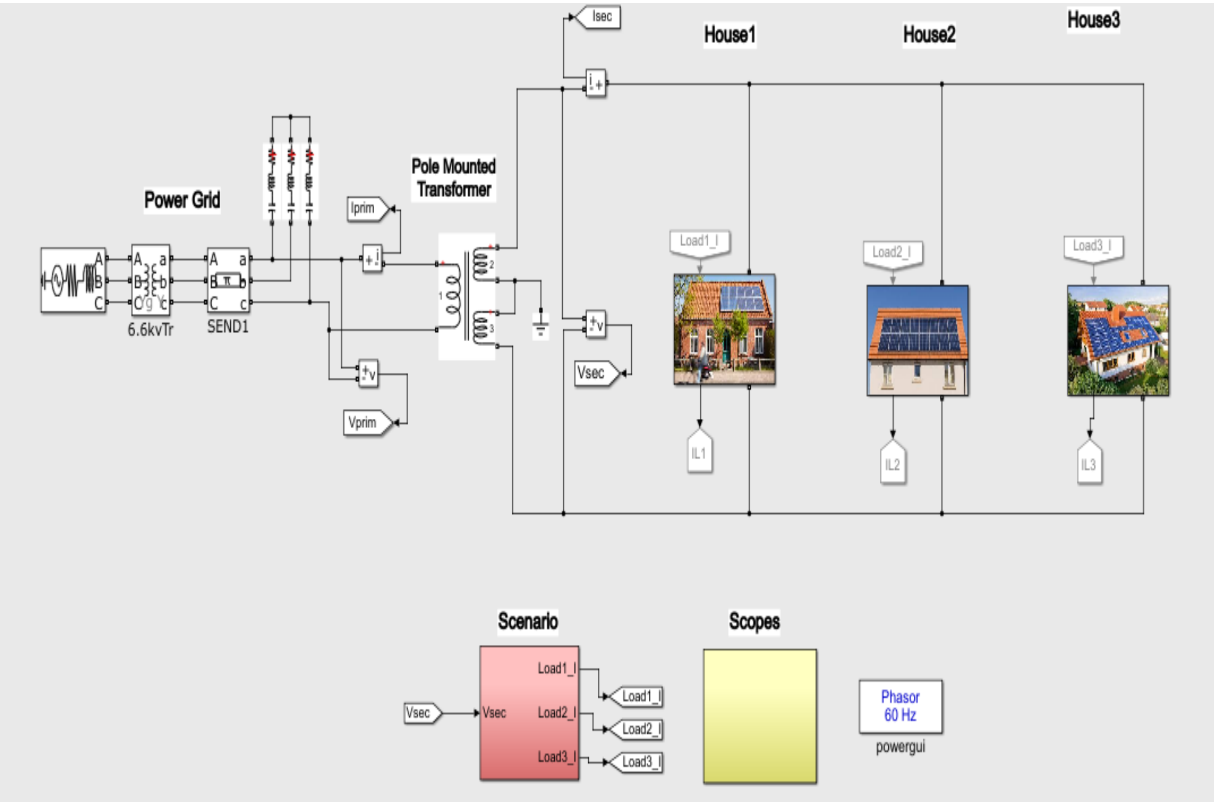

Figure 3.5 Simulink model for Power Grid supplying variable load

3.3.1.1 Description

The system consists of a power grid that provides electricity to three ordinary houses, each with a power consumption rate of 2 kW. The power from the grid is transmitted through a transformer that is mounted on a post. The transformer's primary function is to lower the voltage from 6.6 kV to 200 V, making it suitable for residential use.

To control the load and adjust the power demand of each house, a controlled current source is employed. This current source enables precise adjustment by injecting a pre-constructed signal into the load. This means that the power consumption of the houses can be actively regulated and tailored to specific requirements.

3.3.1.2 Results

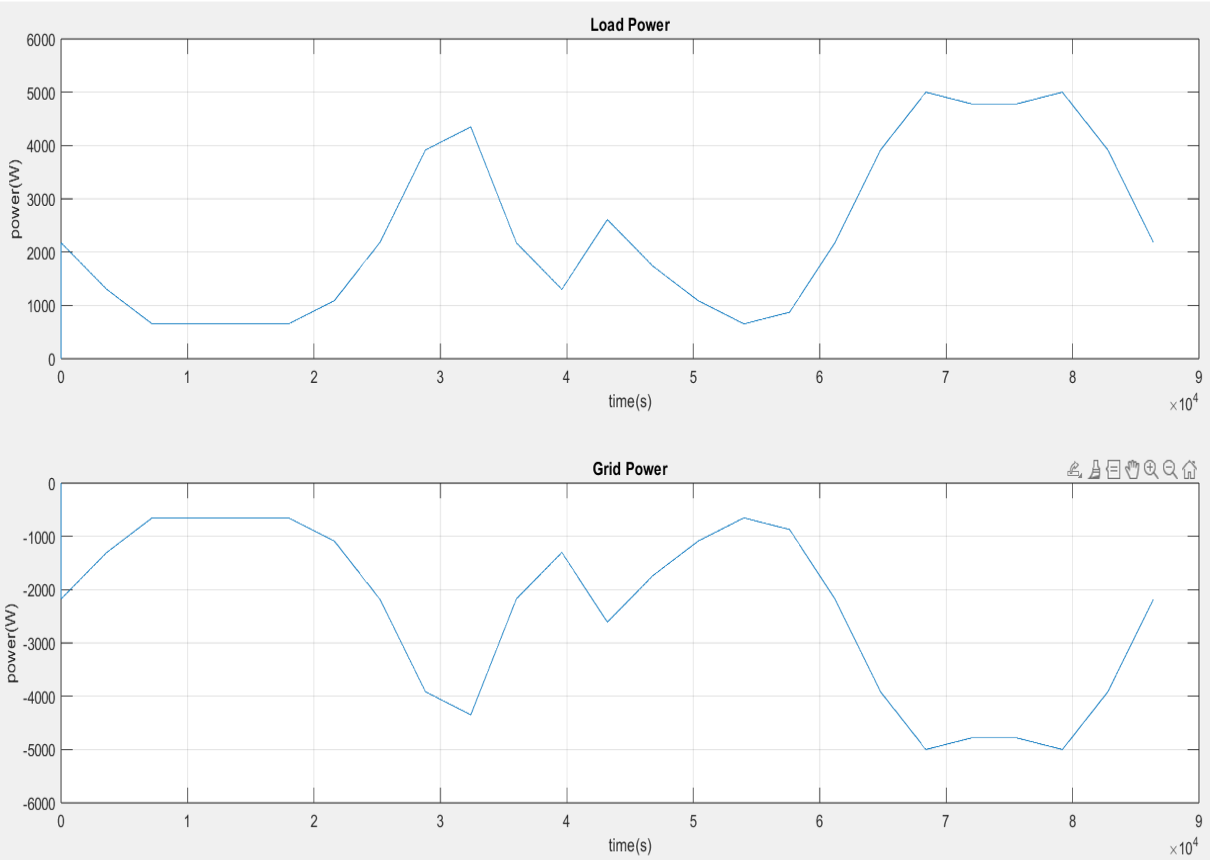

Figure 3.6 Comparing the load demand with the output Grid power

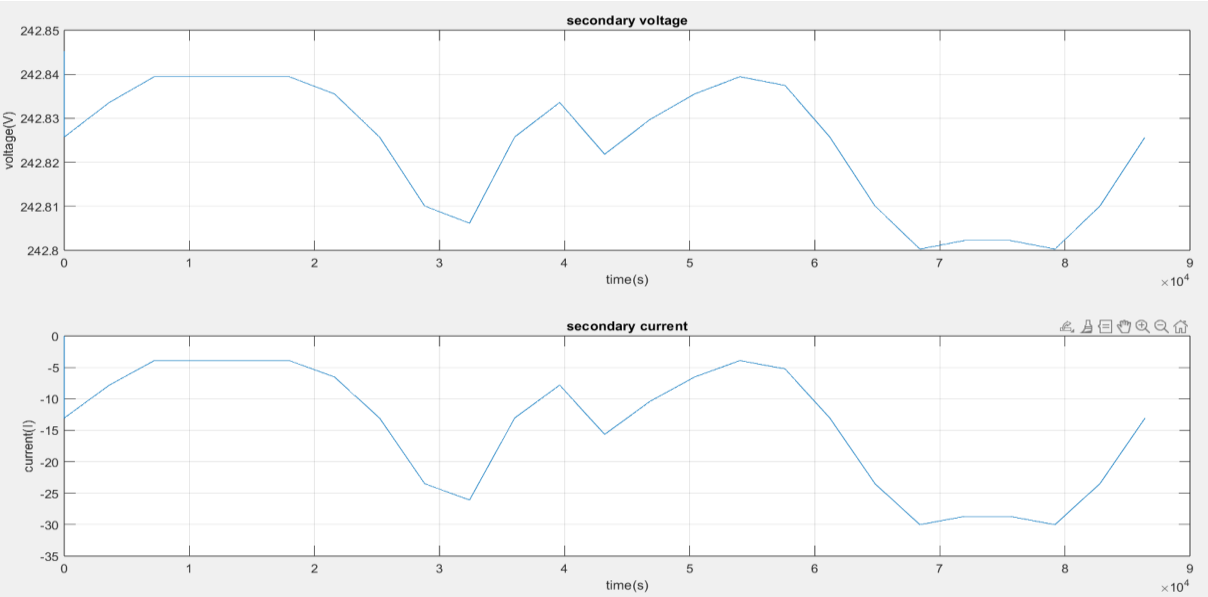

Figure 3.7 The output Voltage and Current of the Grid

From the provided information, Figure 3.6 shows that our grid is meeting the load demands. It indicates that as the load power varies, grid power also changes.

We can see also from V and I plots in Figure 3.7 that the voltage remains almost constant while the current is adjusted accordingly to satisfy the load power requirements. This dynamic response of the grid ensures that the load receives the necessary power supply without compromising the stability of the grid.

3.3.2 Grid + PV system + load

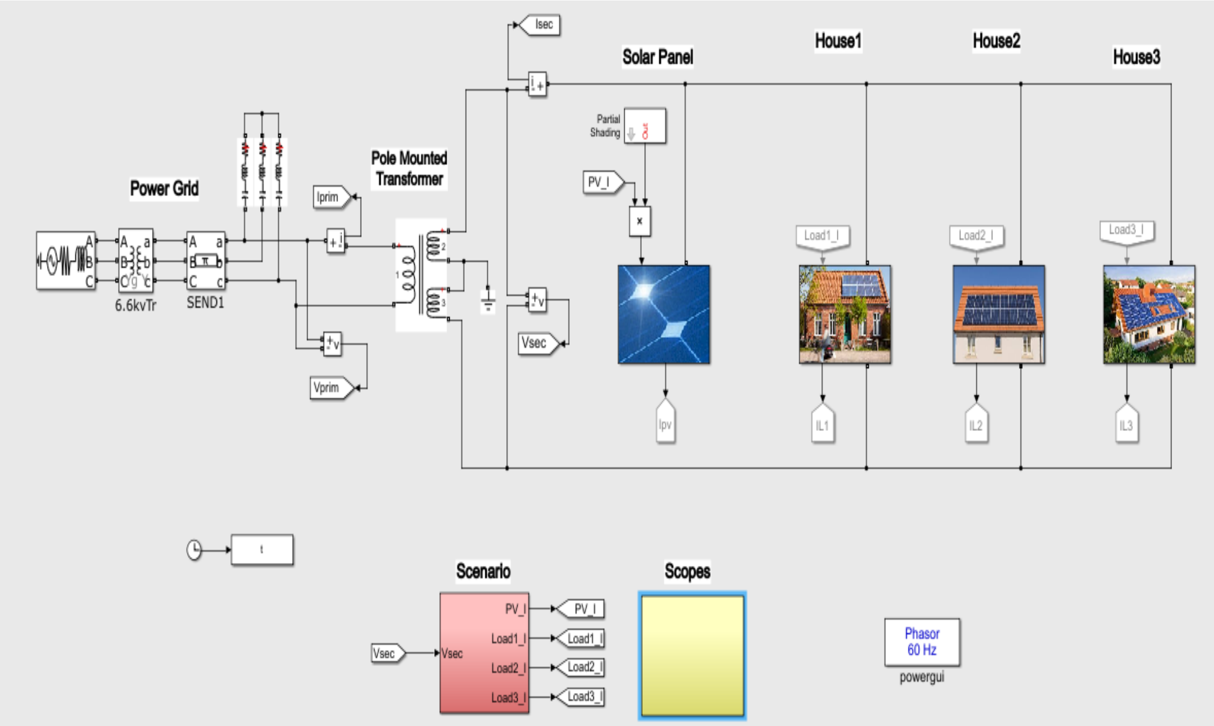

Figure 3.8 Simulink model for Power Grid, PV and Load

3.3.2.1 Description

In this case our system constitutes of a power grid that serves as the main source of electricity. It supplies power to three ordinary houses, with each house having a power consumption rate of 2.5 kW. Additionally, there is a photovoltaic (PV) system installed that can generate 5 kW of power give or take.

The power grid serves as the primary source of electricity to ensure a reliable and consistent supply of electricity to the houses, meeting their daily energy requirements, on the other hand the PV system contributes additional power when available, it generates electricity from sunlight to produce extra energy.

3.3.2.2 Results

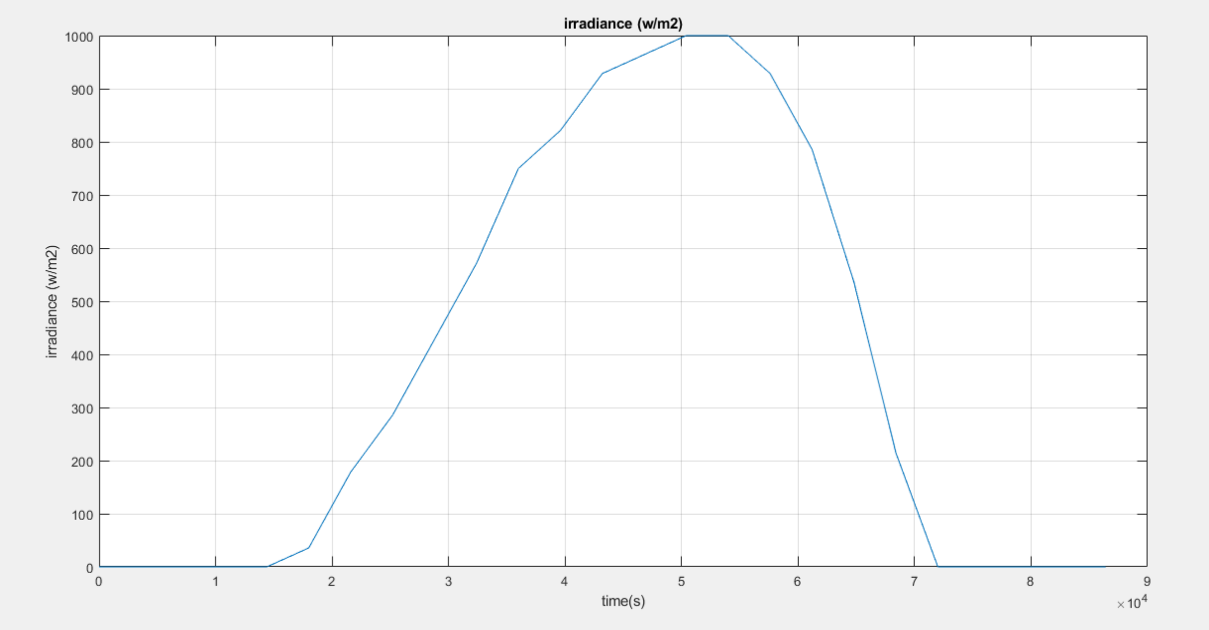

Figure 3.9 Solar irradiance

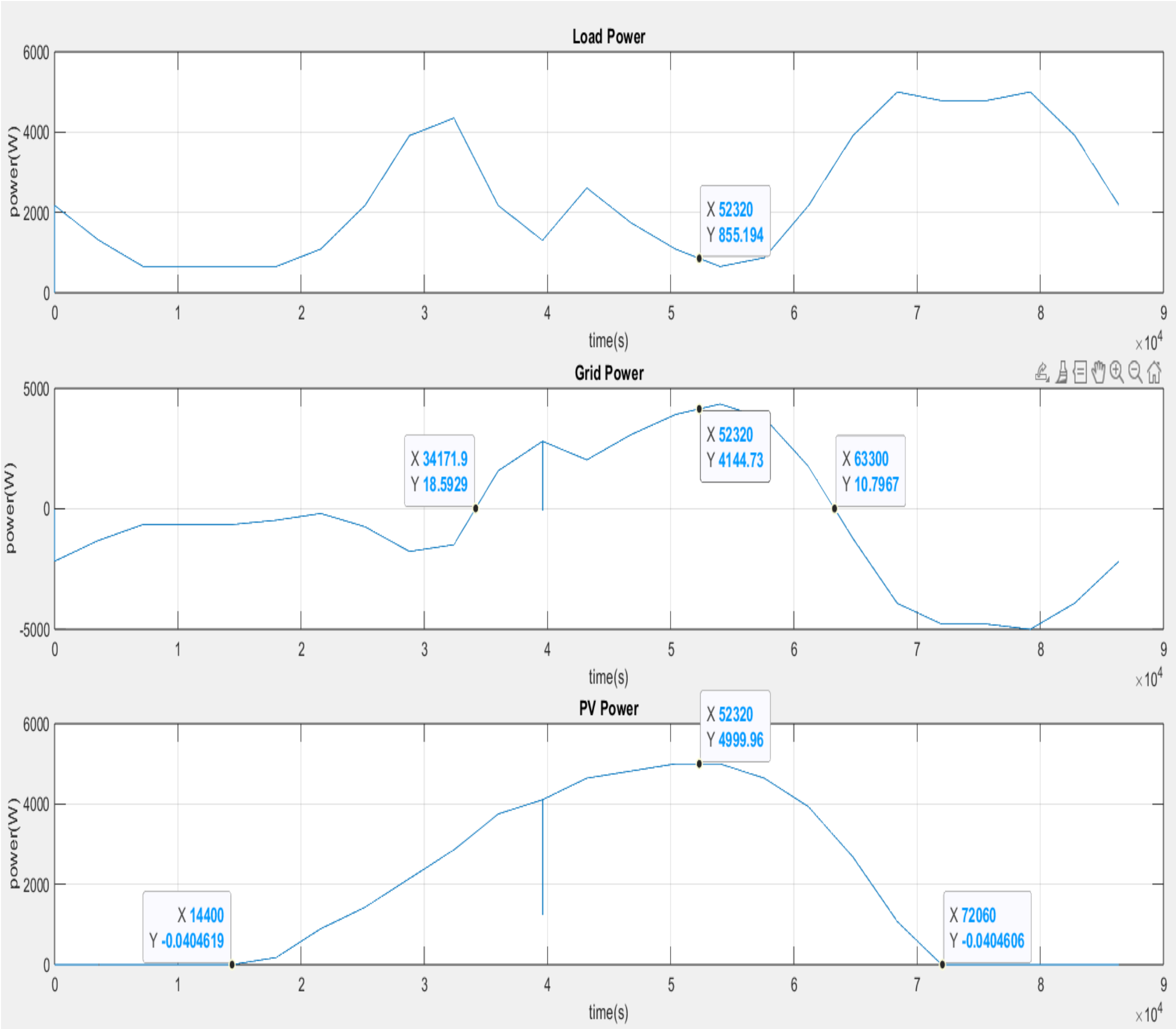

Figure 3.10 PV, Grid and Load Power variations

During the first four hours of the morning and from 8 pm to midnight, when there is no sunlight and zero irradiation (0 W/m²) as shown in **figure 3.9**, the PV system's output is zero, and the power grid becomes the sole power source.

From 4 am to 8 pm, as irradiation increases, the power output of the PV system begins to rise. Concurrently, the power drawn from the grid varies based on the PV power and the load demand. Our system efficiently manages the power distribution between the two sources, prioritizing the renewable energy from the PV system to supply the load directly.

As PV power increases from 4 am, the grid-supplied power gradually decreases until it reaches zero at 9:49 am. This indicates that the PV system generates enough power to meet the entire load demand.

From 9:49 am to 6 pm, the surplus energy generated by the PV system is fed back into the grid. The generator switches from generating to motoring mode to consume the excess energy. To manage this surplus energy effectively, incorporating an energy storage system becomes necessary.

At exactly 2:53 pm, the load is absorbing 855.194 W, while the PV system generates 4999.96 W. Therefore, the power grid absorbs the surplus power:

$$P_{PV} - P_{Load} = 4999.96 \text{ w} - 855.194 \text{ w} = 4144.766 \text{ w}$$

According to Figure 3.10, the same result is observed, with a surplus power of 4144.73 W.

By adding an energy storage system, the surplus energy generated by the PV system can be stored rather than dissipated. This stored energy can then be used during periods of low PV generation or high load demand, ensuring a more efficient utilization of the generated energy. This concept will be explored further in the next section.

3.3.3 Grid + PV system + load+ ESS

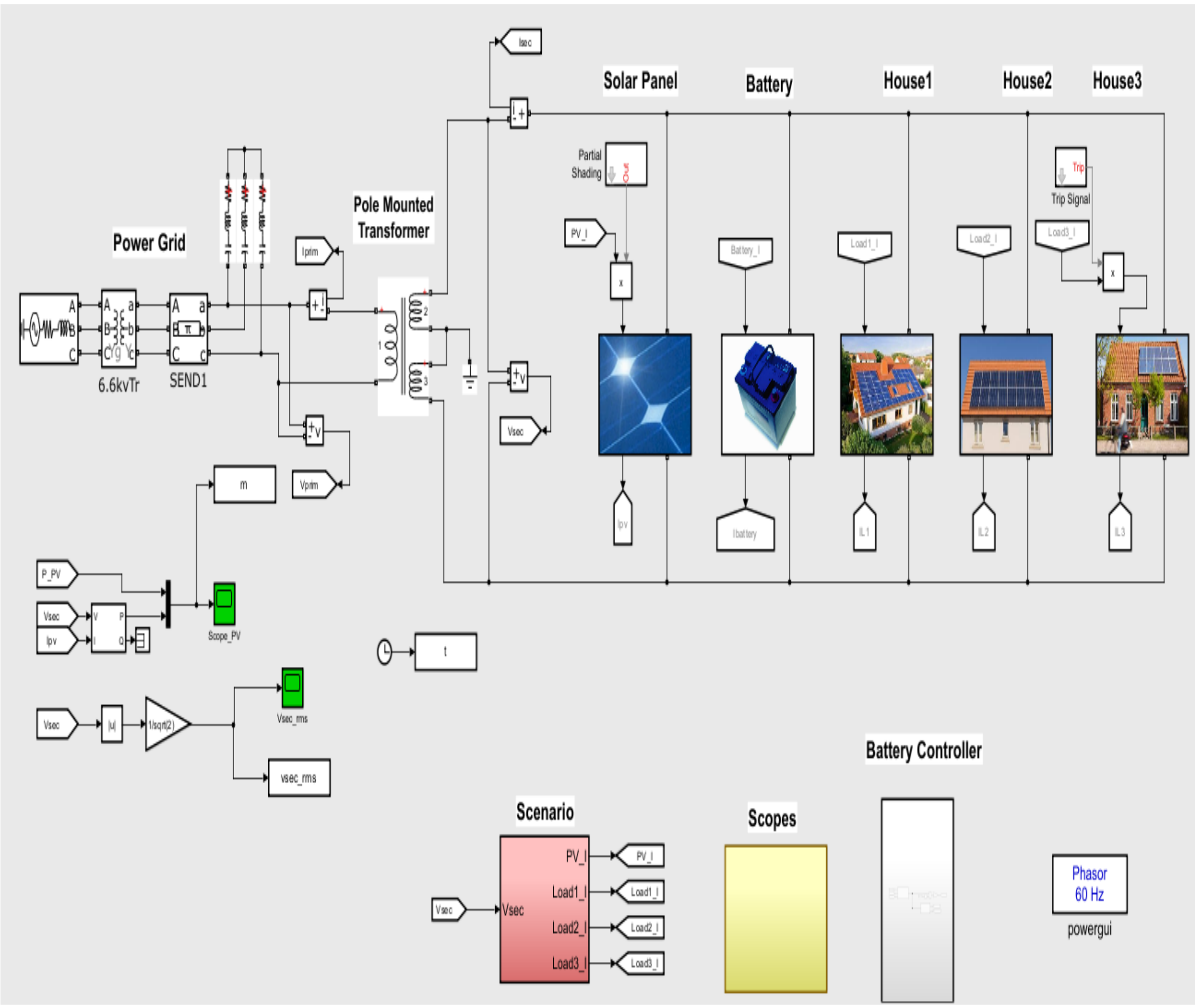

Figure 3.11 Simulink model for Power Grid, PV, Load and ESS

3.3.3.1 Description

The storage battery is controlled by a battery controller. It absorbs surplus power when there is excess energy in the micro-network, and provides additional power if there is a power shortage in the micro-network. Three ordinary houses consume energy (maximum of 2.5 kW) as electric charges.

The solar power generation and storage battery are DC power sources that are converted to single-phase AC. The control strategy assumes that the microarray does not depend entirely on the power supplied by the power grid, and the power supplied by the solar power generation and storage are sufficient at all times.

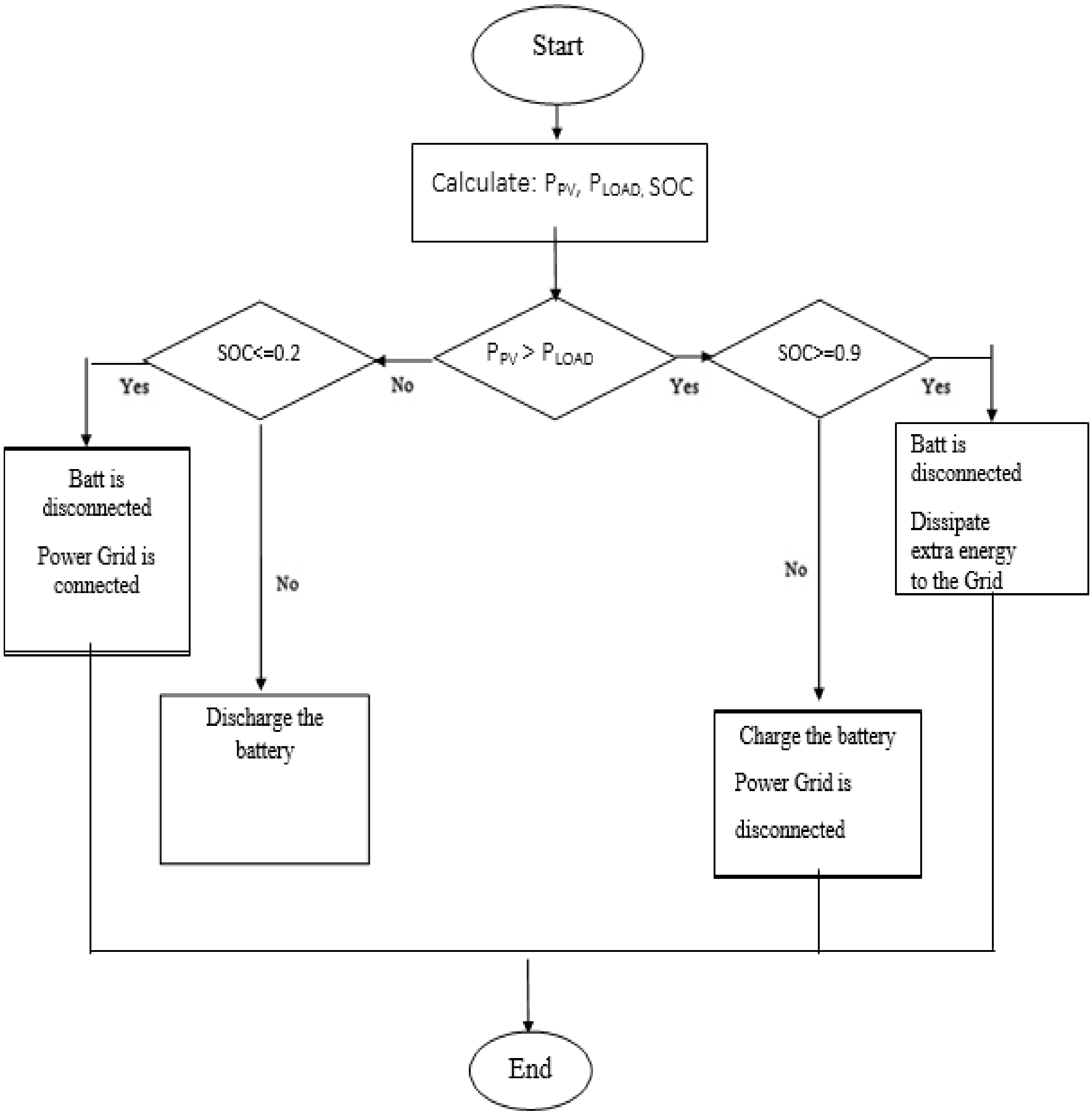

Figure 3.12 Power management flowchart of the system.

3.3.3.2 Results

- **Average load**

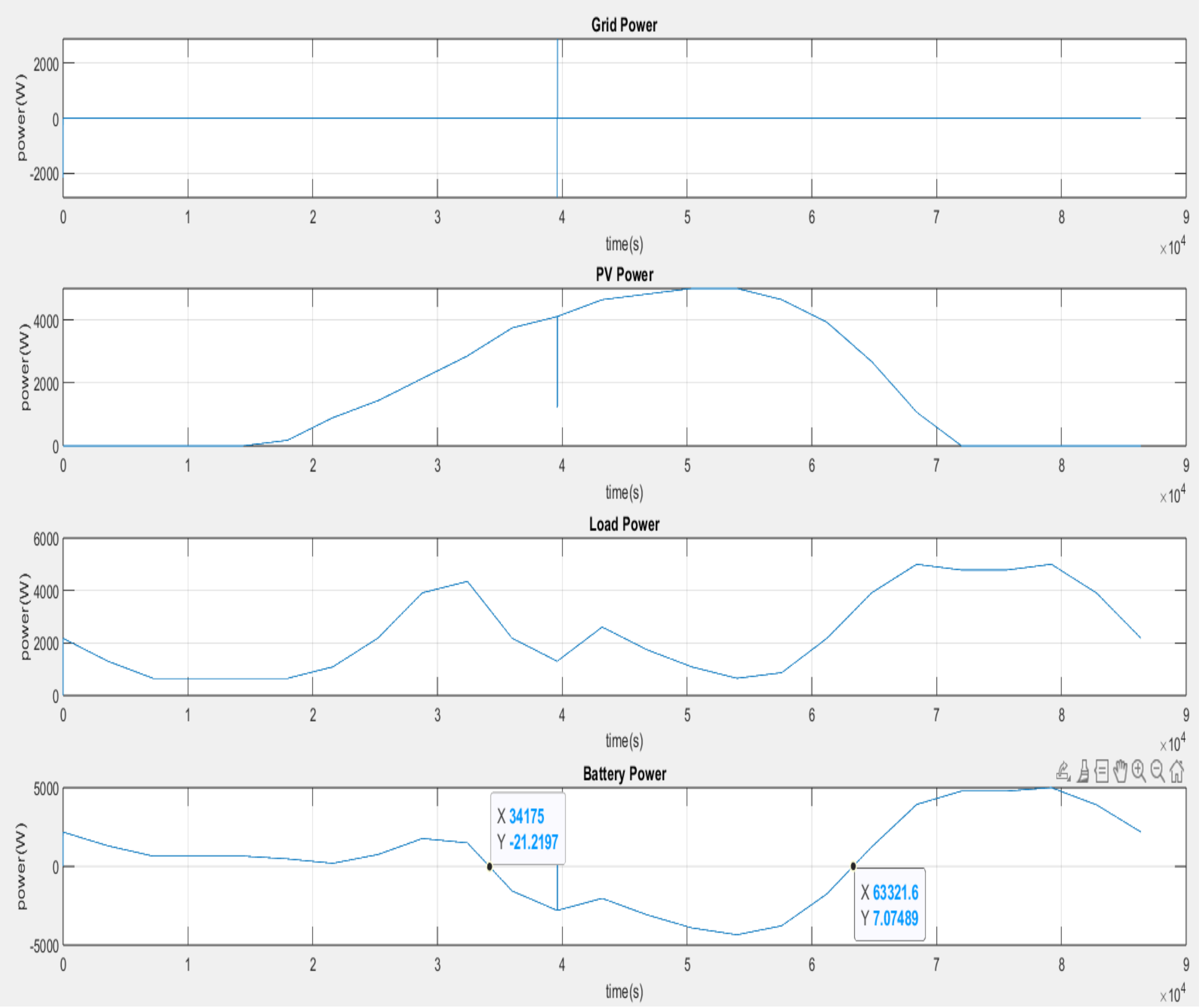

Figure 3.13 PV, Grid, Average Load and ESS Power variations

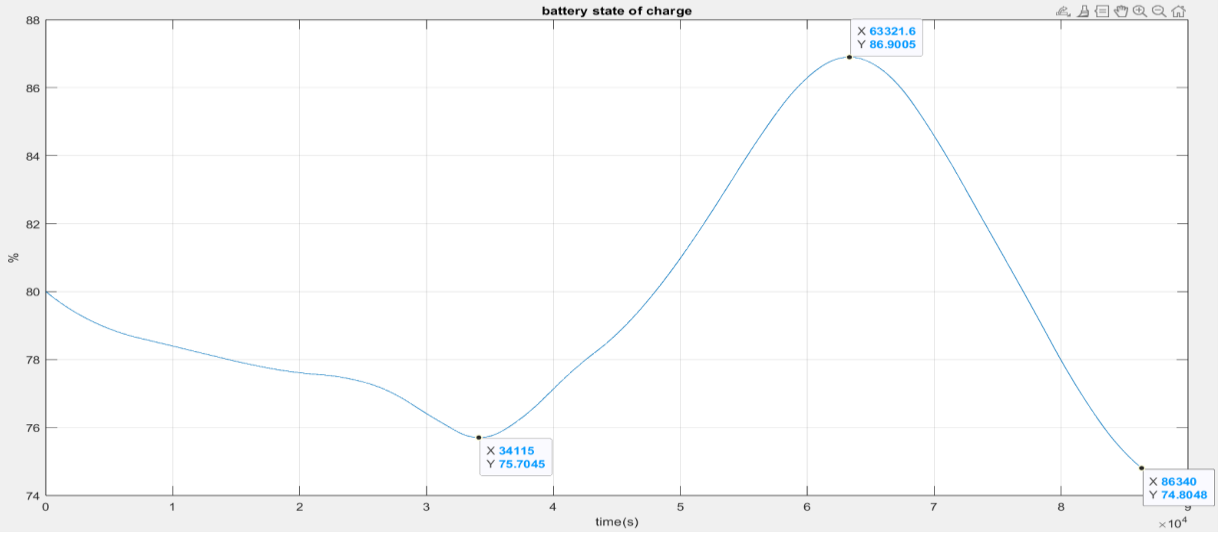

Figure 3.14 Battery SOC

As illustrated in Figure 3.13, the addition of a battery to the system eliminates the need for power generation from the grid over the entire 24-hour period. The photovoltaic (PV) system generates enough power to meet the load demand independently. Consequently, any excess power produced by the PV panels is stored in the battery, ensuring that all generated power is utilized efficiently.

From midnight to 4 am, the battery supplies the loads, with an initial charge level assumed to be at 80%.

From 4 am to 9:49 am, as the PV system begins generating power, both the battery and the solar panels feed the load.

From 9:49 am to 6 pm, there is a surplus of power from the PV system. During this period, the PV panels supply the load directly, and the battery stores the surplus energy. As illustrated in Figure 3.14, the battery charge level increases from 75.7% to 86.9%.

From 6 pm to midnight, as the PV power decreases and reaches zero by 8 pm, the battery once again supplies the load. Consequently, the battery charge decreases from 86.9% to 74.8%.

The above results are for a moderate load; now we will examine the case where the load is too high.

- **High load**

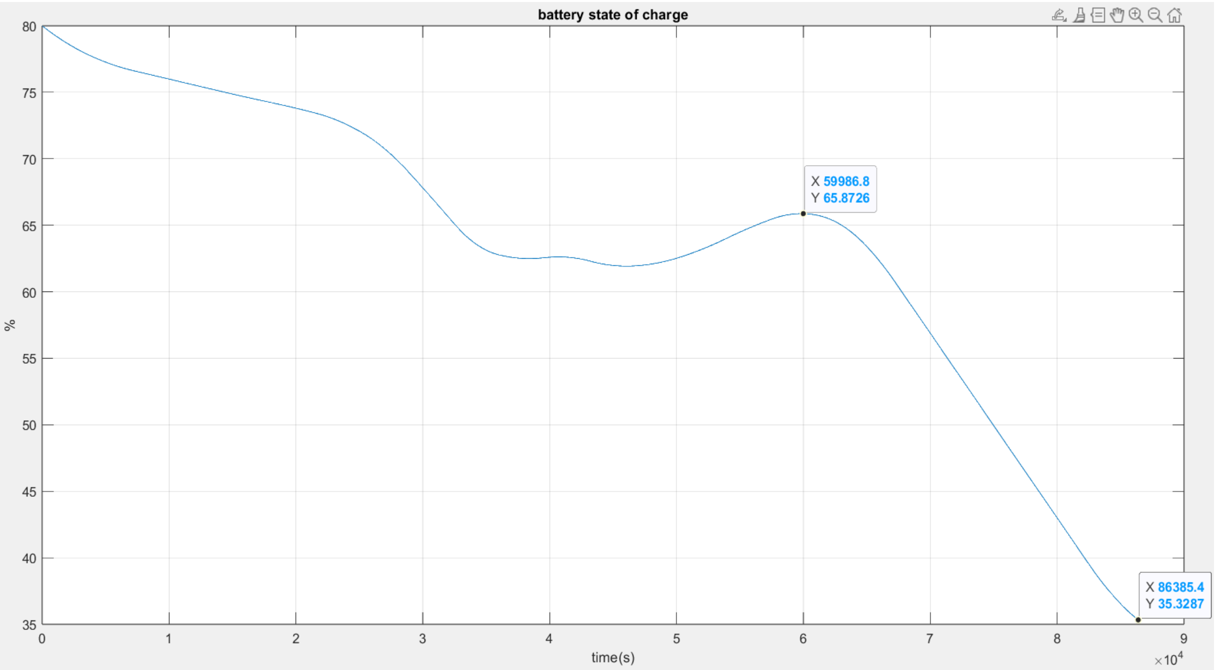

Figure 3.15 Battery SOC

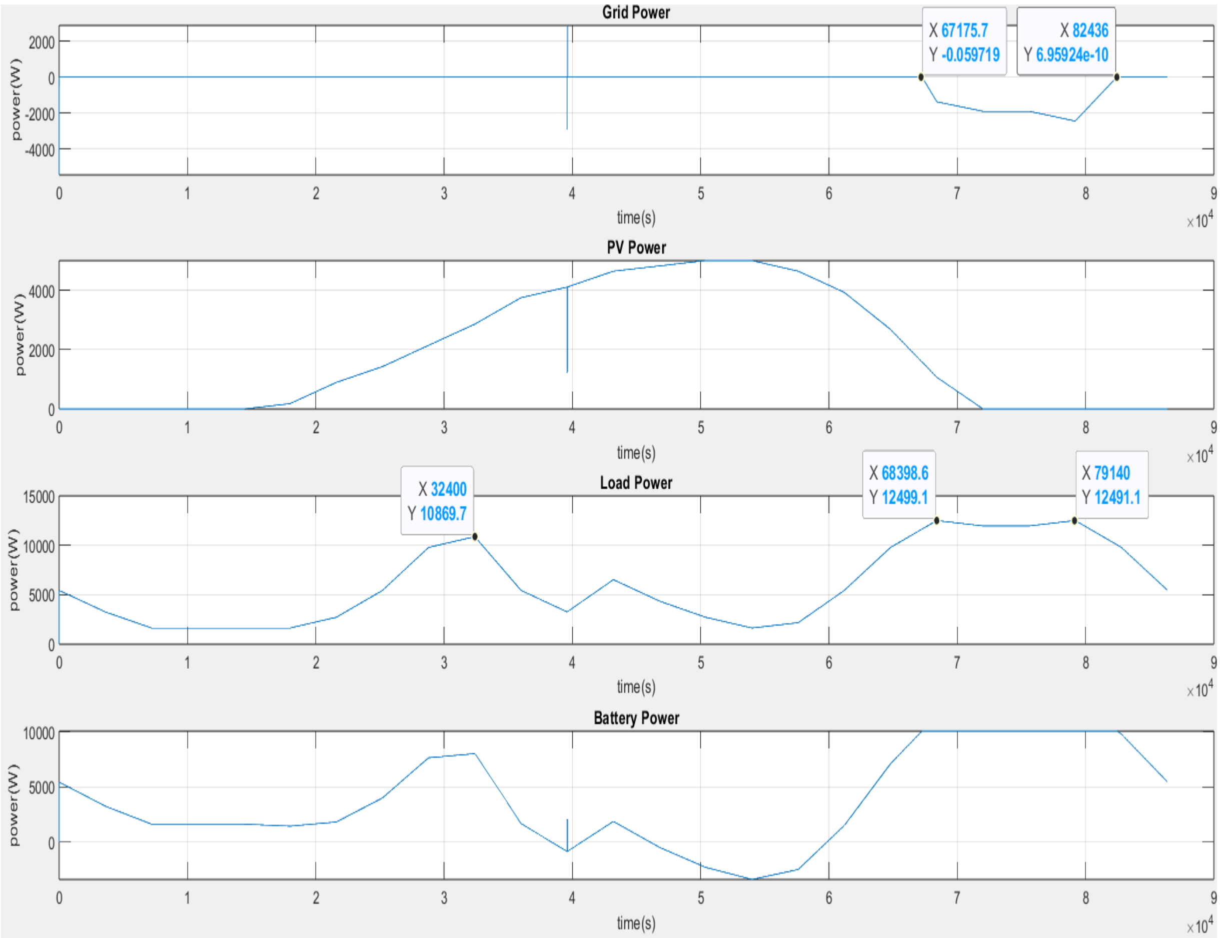

Figure 3.16 The Power Graphs of: Grid, PV, high Load and ESS respectively

In this section, the amount of electric power load reaches peak consumption at 9 am (10,869.7 W), 7 pm, and 10 pm (12,491.1 W).

As illustrated in Figure 3.16, unlike the previous grid power graph, this time the PV and battery power are insufficient to meet the load demand. Consequently, between 6:30 pm and 10:40 pm, the power grid generates approximately 2 kW to satisfy the load demand.

Additionally, the increased load impacts the battery's state of charge, causing it to decrease to 35.32% by the end of the day.

3.4 Conclusion

The simulation of the photovoltaic (PV) system with battery storage and grid support demonstrates the dynamic interactions and effectiveness of the system under different load conditions throughout the day. Key findings from the simulation results include:

Under moderate load conditions, the PV system, supplemented by the battery, effectively meets the load demand without requiring additional power from the grid.

During periods of surplus PV generation, excess energy is efficiently stored in the battery, enhancing energy utilization and reducing reliance on the grid.

When the load demand increases significantly, the combined output of the PV system and the battery becomes insufficient to meet the load requirements.

During these high load periods, particularly between 6:30 pm and 10:40 pm, the grid supplies approximately 2 kW to bridge the gap and satisfy the load demand.

The increased load also results in a significant decrease in the battery's state of charge, which drops to 35.32% by the end of the day. This indicates a higher rate of battery discharge and highlights the need for grid support under such conditions.

The integration of the battery storage system proves beneficial during low irradiation periods (midnight to 4 am and 8 pm to midnight), as the battery can supply the load, reducing grid dependence.

During peak sunlight hours (9:49 am to 6 pm), the PV system generates surplus energy, which is stored in the battery, ensuring efficient energy use and preparing the system for periods of low PV generation.

The system prioritizes the use of renewable energy from the PV panels, directly supplying the load whenever possible and storing excess energy in the battery.

The effective management of energy between the PV system, battery, and grid ensures that load demands are consistently met, while maximizing the use of renewable energy and minimizing grid reliance.

Overall, the simulation results demonstrate that the hybrid PV system, equipped with battery storage and grid support, is capable of managing varying load conditions effectively. Under moderate loads, the system can operate independently of the grid for extended periods, while under higher loads, the grid serves as a necessary backup to ensure uninterrupted power supply. The incorporation of an energy storage system enhances the system's resilience and efficiency, making it a viable solution for sustainable energy management.

CHAPTER 4: *COST ANALYSIS OF A HYBRID* ENERGY *SYSTEM USING HOMER PRO SOFTWARE*

4.1 Introduction

This chapter focuses on the design and analysis of a hybrid energy system comprising photovoltaic (PV) panels, a battery storage system, a diesel generator, and a converter, tailored to meet the energy needs of a community load. By integrating multiple energy sources, the hybrid system aims to optimize the balance between energy generation, storage, and consumption, thereby enhancing system efficiency, reliability, and cost-effectiveness.

HOMER Pro, a leading software tool for simulating and optimizing hybrid energy systems, is utilized to perform the analysis. This tool allows for the detailed modeling of various system configurations and provides insights into the technical and economic performance of each setup. The objective of this project is to determine the optimal configuration that minimizes costs while ensuring a high level of renewable energy penetration and reliability.

The significance of this study lies in its potential to contribute to the growing body of knowledge on hybrid energy systems, particularly in the context of community-scale applications. By demonstrating the feasibility and benefits of integrating PV, battery storage, and a generator, this project aims to provide a practical solution for communities seeking to transition towards sustainable energy systems.

In the subsequent sections, we will delve into the specifications of each component, the setup of the simulation, the results obtained, and the conclusions drawn from the analysis. Through this comprehensive approach, we aim to provide a clear understanding of the design and performance of the hybrid energy system, highlighting its potential as a viable solution for community energy needs.

4.2 HOMER Pro Overview

HOMER Pro is a sophisticated and versatile software tool developed by the National Renewable Energy Laboratory (NREL) for the purpose of modeling and optimizing hybrid renewable energy systems. It is widely used by researchers, engineers, and planners to design and analyze energy systems that integrate a variety of power sources, including solar, wind, batteries, and conventional generators [28].

HOMER Pro stands out due to its ability to simulate the complex interactions between different components of a hybrid energy system. By allowing users to input detailed specifications for each component, HOMER Pro can model the performance of the system under various scenarios and load profiles. The software is capable of :

- **System Design and Optimization:** HOMER Pro evaluates thousands of potential system configurations to identify the most cost-effective and reliable design. It considers both capital and operating costs, as well as technical performance metrics.
- **Economic Analysis:** The software calculates key economic indicators such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and return on investment. This helps users assess the financial viability of different system designs.
- **Sensitivity Analysis:** HOMER Pro allows users to perform sensitivity analyses on critical variables such as fuel prices, interest rates, and renewable resource availability. This helps in understanding how changes in these variables affect system performance and costs.
- **Renewable Resource Integration:** The software models the integration of renewable resources like solar and wind, accounting for their variability and intermittency. It can simulate the effect of different renewable penetration levels on system reliability and economics.
- **Load Management:** HOMER Pro can model diverse load profiles, including residential, commercial, and industrial loads. It helps in understanding the demand patterns and how different energy sources can meet these demands effectively.

In the context of hybrid energy systems, HOMER Pro's comprehensive modeling capabilities are invaluable. It allows for the simulation of systems that combine renewable sources with conventional generators and storage solutions, providing a detailed analysis of their performance. Specifically HOMER Pro can :

- **Optimize Component Sizing:** Determine the optimal size of PV panels, battery storage, and generators to meet the load requirements efficiently.
- **Evaluate Operational Strategies:** Analyze different operational strategies for managing the energy flow between generation, storage, and consumption to minimize costs and maximize reliability.
- **Environmental Impact Assessment:** Assess the environmental benefits of incorporating renewable energy by estimating reductions in greenhouse gas emissions and fuel consumption.

The decision to use HOMER Pro for this project is driven by its robust analytical capabilities and its widespread acceptance in the field of hybrid energy system design. The software's ability to integrate detailed technical and economic analyses makes it an ideal tool for evaluating complex hybrid systems. Its user-friendly interface and extensive documentation further enhance its utility, making it accessible to both novice and experienced users.

HOMER Pro provides a comprehensive platform for designing, simulating, and optimizing hybrid energy systems, making it an essential tool for this project. Its ability to handle complex system interactions and perform detailed economic analyses ensures that the results are both accurate and practical, guiding the development of efficient and sustainable energy solutions for community loads [29].

4.3 Component specifications

In designing a hybrid energy system, it is crucial to carefully select and specify each component to ensure optimal performance and reliability. This section provides detailed specifications for the key components of our system: photovoltaic (PV) panels, battery storage, a diesel generator, and a converter. Each component has been chosen based on its suitability for the project's goals, and their specifications are tailored to meet the energy demands of the community load effectively. Below are the detailed descriptions and specifications of each component.

4.3.1 The PV array

Table 4.1 PV array specifications

Description	Specification
Name	Generic flat plate PV
Panel type	Flat plate
Rated capacity (Kw)	1
Manufacturer	Generic
Capital cost (DA)	400,000
Replacement cost (DA)	40,000
Operating & Maintenance cost (DA)	3,000
Life time (years)	15

4.3.2 Battery storage system

Table 4.2 Battery specifications

Description	Specification
Name	Gildemeister 30kW-40kW CELLCUBE FB 30-40
Nominal voltage (V)	48
Nominal capacity (kWh)	40
Nominal capacity (Ah)	833
Roundtrip efficiency (%)	64
Maximum charge current (A)	583
Maximum discharge current (A)	911
Capital cost (DA)	200,000
Replacement cost (DA)	10,000
Operating & Maintenance cost (DA)	1,000
Life time (years)	15

4.3.3 Generator

Table 4.3 Generator specifications

Description	Specification
Name	Autosize Genset
Fuel	Diesel
Fuel curve intercept	1.45 L/hr
Fuel curve slope	0.236L/hr/kW
Lower heating value (MJ/kg)	43.2
Density (kg/m^3)	820
Carbon content (%)	88
Capital cost (DA)	94,000
Replacement cost (DA)	5,000
Operating & Maintenance cost (DA/hr)	0.03
Fuel cost (DA/L)	30
Life time (years)	15

4.3.4 Converter

Table 4.4 Converter specifications

Description	Specification
Relative capacity (%)	90
Inverter input efficiency (%)	95
Inverter output efficiency (%)	95
Capital cost (DA)	13,000
Replacement cost (DA)	2,000
Operating & Maintenance cost (DA)	1,000
Life time (years)	15

4.3.5 Controller

4.3.5.1 Load following strategy

The load following stratefy is a dispatch strategy whereby whenever a generator operates, it produces only enough power to meet the primary load. Lower priority objectives such as charging the storage bank or serving the deferrable load are left to the renewable power sources. The generator may still ramp up and sell power to the grid if it is economically advantageous.

4.3.5.2 Cycle charging strategy

The cycle charging strategy is a dispatch strategy whereby whenever a generator needs to operate to serve the primary load, it operates at full output power. Surplus electrical production goes toward the lower-priority objectives such as, in order of decreasing priority: serving the deferrable load, charging the storage bank, and serving the electrolyzer.

4.4 Simulation setup

4.4.1 Load profile

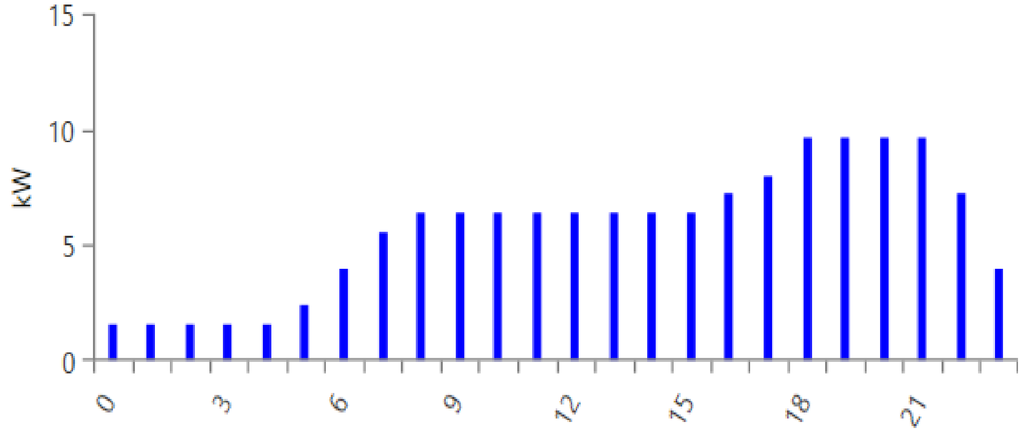

Figure 4.1 Daily load profile

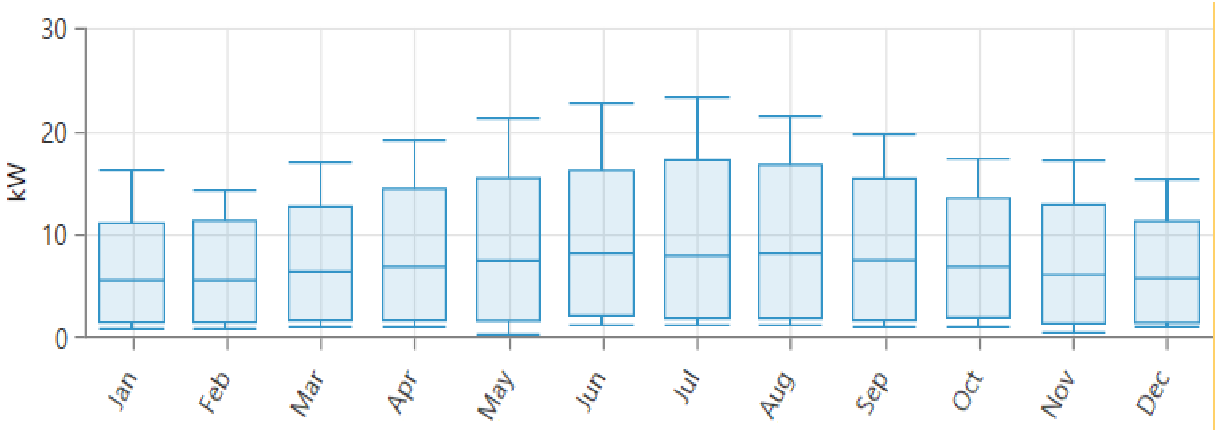

Figure 4.2 The seasonal load profile

Figure 4.3 The location of the community load

The community load profile is a critical aspect of this study, representing the energy consumption patterns of a community located in Boumerdes, Algeria (coordinates: 36°45.5'N, 3°28.4'E) as shown in Figure 4.3. The daily load profile, depicted in Figure 4.1, illustrates the typical energy demand over a 24-hour period. From 1 to 6 AM, the usage is low, about 2 kW. From 7 AM to 4 PM, the demand rises to about 7 kW, and from 5 PM to 10 PM, it peaks at approximately 10 kW. The load then reduces to less than 5 kW from 10 PM to midnight. Additionally, the seasonal load profile in Figure 4.2 shows that the months of May, June, July, and August experience higher load demands, reaching up to 24 kW in July. These data are downloaded from HOMER Pro's NASA prediction models. This detailed load profile information is essential for accurately simulating and optimizing the hybrid energy system to ensure it meets the community's needs effectively and efficiently.

4.4.2 System configuration

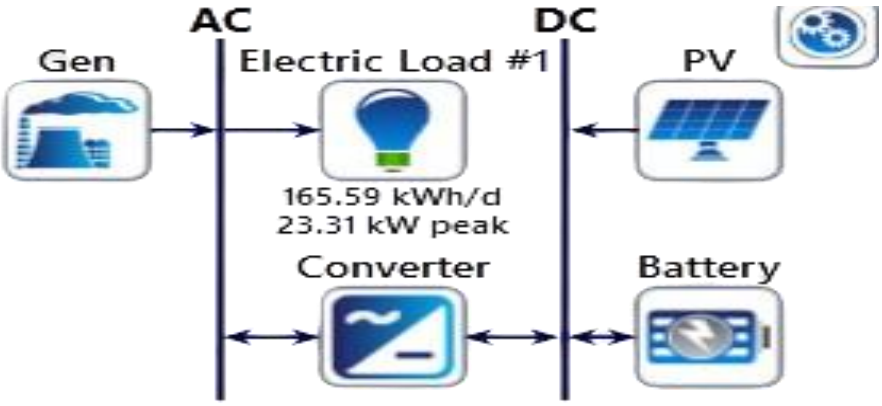

Figure 4.4 Microgrid System Configuration and Component Interconnection

The system configuration of the microgrid is meticulously designed to ensure efficient and reliable operation while meeting the energy demands of the community load. As illustrated in Figure 4.4, the components are interconnected to form a cohesive system. The PV panels, along with the battery storage system, are connected to the DC bus, allowing for direct current energy generation and storage. This arrangement optimizes the utilization of solar energy and enables efficient management of energy storage for use during periods of low sunlight or high demand. On the other hand, the generator and electric load, with a daily consumption of 165.59 kWh and a peak demand of 23.31 kW, respectively, are connected to the AC bus. This setup ensures that the generator can supply power to the electric load when renewable energy sources are insufficient to meet demand. Additionally, the converter, located at the interface between the DC and AC buses, facilitates the bi-directional conversion of power, ensuring compatibility and seamless integration between the different energy sources and loads. By strategically configuring the microgrid components in this manner, the system can effectively balance supply and demand, optimize energy utilization, and enhance overall system resilience and stability.

4.4.3 Solar resources

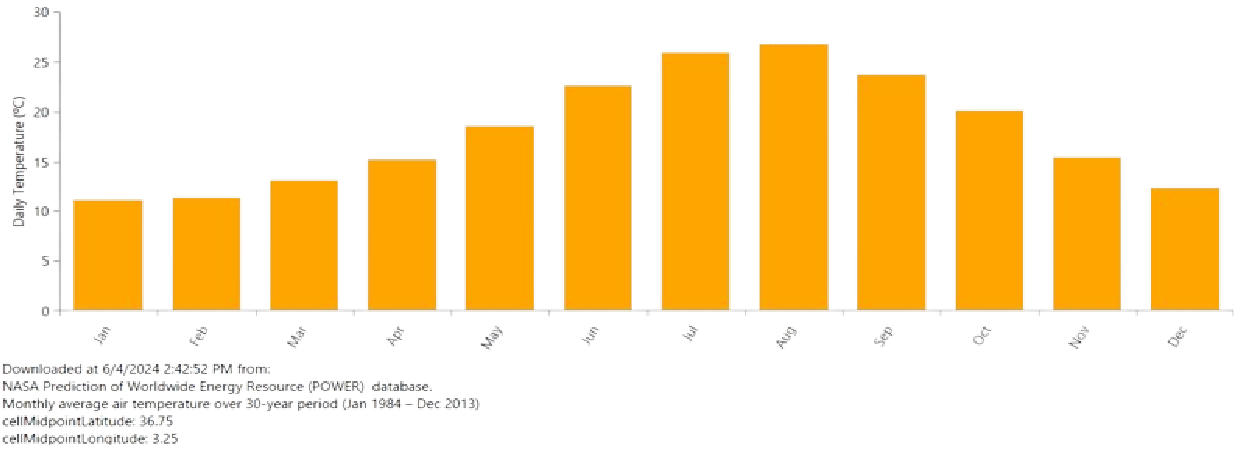

Figure 4.5 Monthly Average Air Temperature Variation

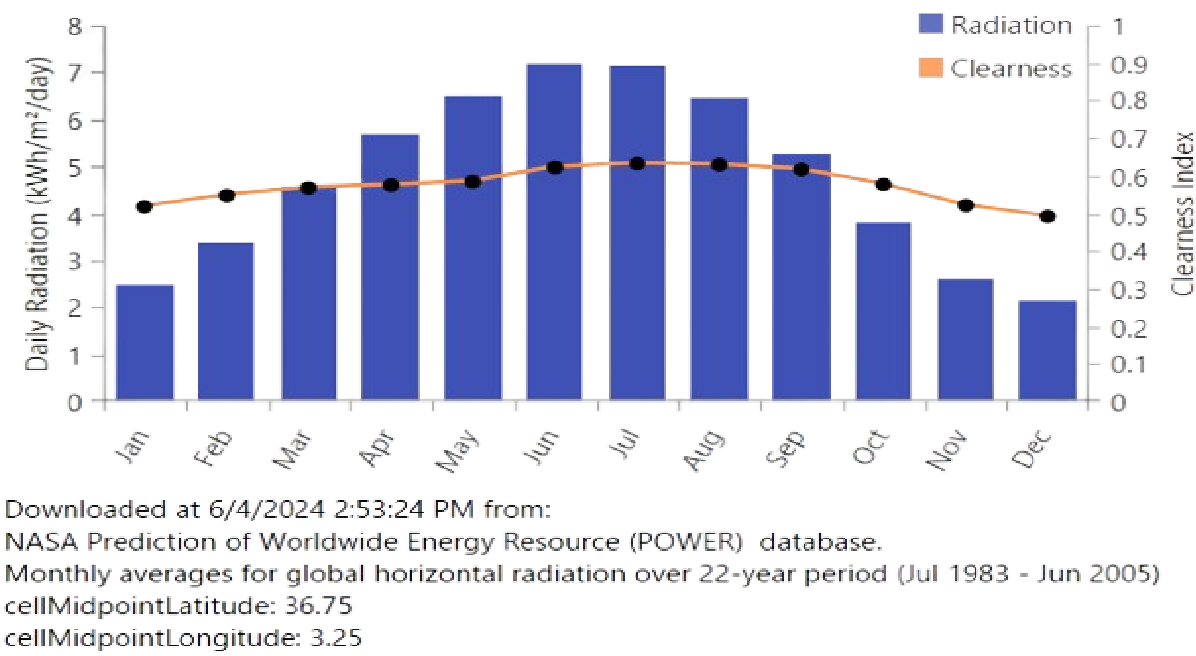

Figure 4.6 Monthly Averages for Global Horizontal Radiation and Clearness Index

Understanding the solar resources available in the area where the community load is situated is crucial for assessing the feasibility and performance of the hybrid energy system. Figure 4.5 presents the monthly average air temperature data, revealing distinct seasonal variations. During the summer months of June, July, August, and September, the average air temperature reaches approximately 25°C, indicating warmer conditions conducive to higher solar energy generation. Conversely, in the winter months, the temperatures range between 10°C and 15°C, reflecting cooler ambient conditions. Figure 4.6 provides insight into the monthly averages for global horizontal radiation and the clearness index of the area. The clearness index, ranging between 0.5 and 0.6 over the year, suggests relatively clear skies and minimal atmospheric obstruction, which enhances the efficiency of solar energy capture. Additionally, the monthly variations in global horizontal radiation highlight the seasonal changes in solar irradiance. From January to November and December, the daily radiation levels average around 2.5 kWh/m²/d and 3.4 kWh/m²/d, respectively. In March, April, and September, the radiation levels increase to around 5 kWh/m²/d, indicating higher solar energy availability. During the peak summer months of May, June, July, and August, the daily radiation varies from 6 to 7 kWh/m²/d, showcasing abundant solar resources during this period. This comprehensive understanding of solar resources is essential for accurately modeling the energy generation potential and optimizing the hybrid energy system to harness the available solar energy effectively. [30]

4.5 Results and discussion

Architecture					Cost			
PV (kW)	Gen (kW)	Battery (#)	Converter (kW)	Dispatch	NPC (DA)	LCOE (DA/kWh)	Operating cost (DA/yr)	CAPEX (DA)
11.9	26.0	1	12.7	CC	DA14.4M	DA15.26	DA589,086	DA5.20M
	26.0	1	8.20	CC	DA14.7M	DA15.56	DA763,840	DA2.76M
	26.0			LF	DA17.6M	DA18.62	DA968,562	DA2.45M
0.865	26.0		0.182	LF	DA17.7M	DA18.78	DA966,751	DA2.63M
64.8		25	21.8	LF	DA20.1M	DA21.35	DA118,962	DA18.3M

Figure 4.7 Cost results for different configurations

The comparative analysis of the five different hybrid system configurations reveals significant variations in economic and operational performance. The PV + Generator + Battery + Converter configuration emerges as the most cost-effective option, with the lowest NPC (14.4M DA) and LCOE- Levelized Cost of Energy - (15.26 DA/kWh), balancing moderate CAPEX- Capital Expenditure - (5.2M DA) and operating costs (589,086 DA). This setup leverages renewable energy from PV to reduce fuel dependency, resulting in lower operational costs compared to generator-only systems. The Generator + Battery + Converter configuration, while having a lower CAPEX (2.76M DA), incurs higher operating costs (763,840 DA) and a slightly higher LCOE (15.56 DA/kWh), making it less attractive. The Generator Only configuration, although having the lowest initial investment, leads to the highest NPC (17.6M DA) and LCOE (18.62 DA/kWh) due to high fuel and maintenance costs. Similarly, the Generator + PV + Converter setup does not significantly improve costs due to minimal PV contribution. The Battery + PV + Converter configuration, despite having the lowest operating cost (118,962 DA), results in the highest CAPEX (18.3M DA) and LCOE (21.35 DA/kWh), making it the least cost-effective. Therefore, the optimal configuration for this community load is the PV + Generator + Battery + Converter setup, offering a balanced approach with the best overall economic performance. All the following results are based on this configuration.

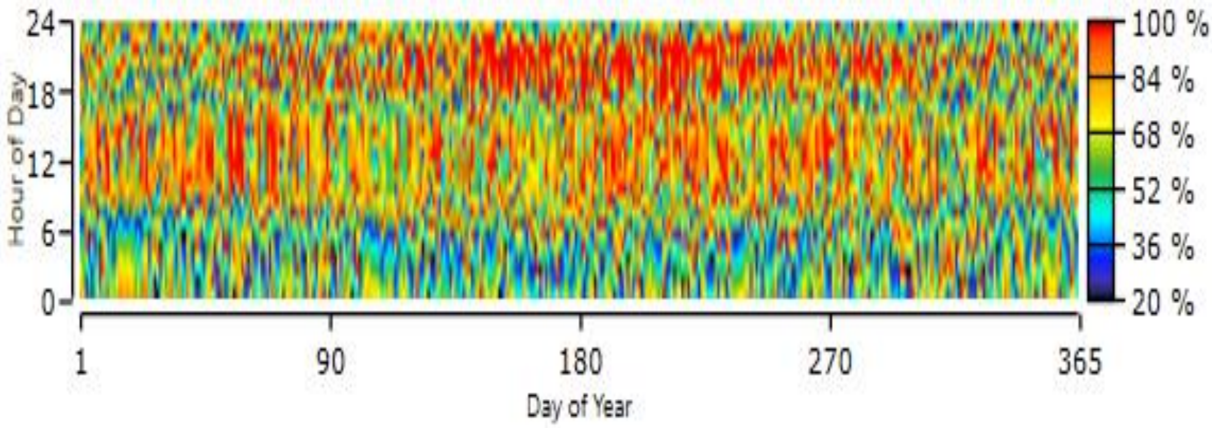

Figure 4.8 Battery state of charge during the year

The analysis of the battery state of charge (SoC) over a 365-day period, as depicted in Figure 4.8, shows a consistent daily pattern. From 1 AM to 7 AM, the battery SoC ranges between 20% and 50%, reflecting the period of reduced solar energy generation and higher reliance on stored energy. During the daytime from 8 AM to 5 PM, the SoC increases to around 70% to 80% due to solar energy generation, which charges the battery. In the evening, from 6 PM to midnight, the SoC decreases slightly to between 50% and 70% as the community load draws power from the battery. Notably, during the summer months, the battery SoC remains around 80% from 8 AM to midnight, indicating higher solar energy generation and reduced battery discharge due to longer daylight hours and increased solar irradiance. This consistent high state of charge during summer underscores the efficiency and reliability of the hybrid system in utilizing solar resources to maintain battery health and ensure energy availability.

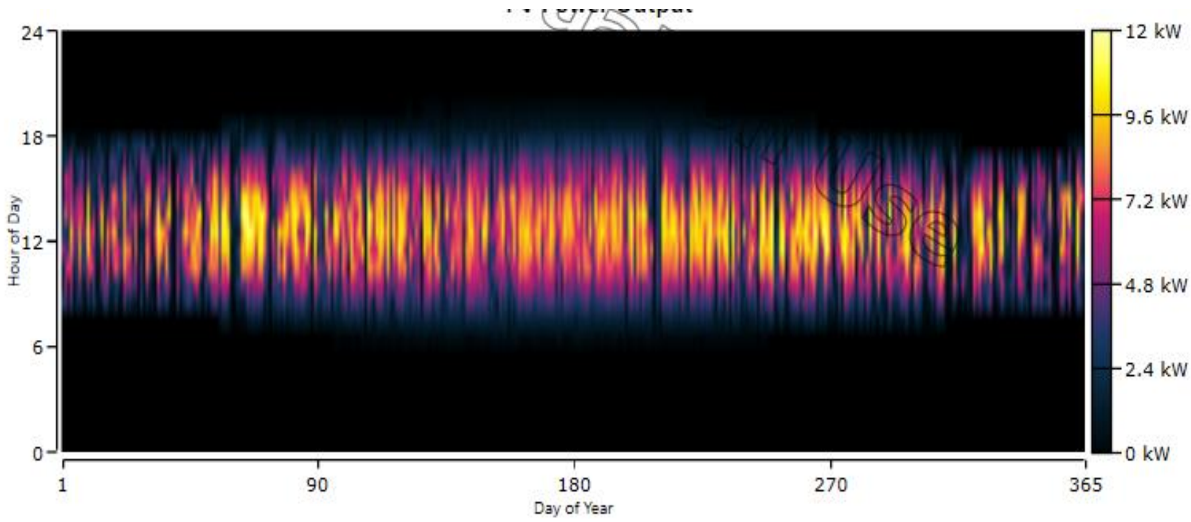

Figure 4.9 PV power output during 365 days

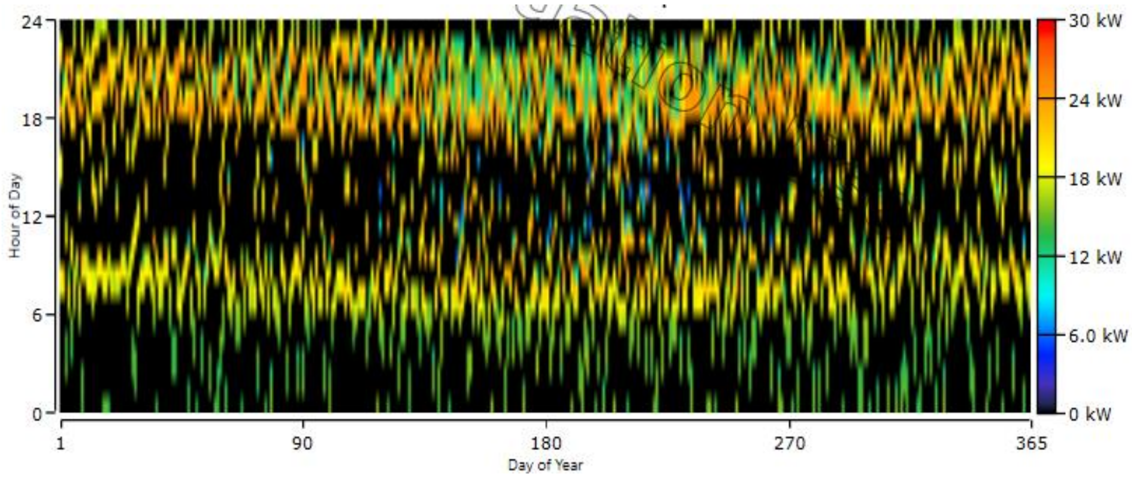

Figure 4.10 Generator power during over 365 days

The PV power output over a 365-day period, illustrated in Figure 4.9, shows a consistent daily pattern of energy generation. From 1 AM to 7 AM and from 6 PM to midnight, the PV system generates no power due to the absence of sunlight. However, from 8 AM to 6 PM, the PV system starts generating power, initially at around 4 kW, peaking between 10 and 12 kW in the middle of the day, and then gradually reducing again by 6 PM. This pattern highlights the reliance on solar irradiance for energy production, with maximum output occurring during peak sunlight hours.

Conversely, Figure 4.10 displays the generator power output over the same period. The generator operates more intensively during early morning and evening hours. From 6 AM to 11 AM, the generator produces around 20 kW, which then reduces to less than 12 kW from 12 PM to 6 PM as the PV system contributes more significantly to the energy supply. From 6 PM to midnight, the generator output increases to more than 24 kW to compensate for the reduced PV output and meet the community's energy demands. During summer days, these patterns adjust slightly, with the generator's output differing due to longer daylight hours and increased PV generation.

The relationship between the PV system and the generator is complementary, with each source compensating for the other's limitations. The PV system provides a significant portion of the energy during daylight hours, reducing the load on the generator. In contrast, the generator supplements the energy supply during early mornings, evenings, and nights when solar energy is unavailable. This interplay ensures a reliable and continuous power supply, optimizing the use of renewable energy while maintaining system stability and meeting the community load effectively.

4.6 Conclusion

This project aimed to design and analyze a hybrid energy system incorporating photovoltaic (PV) panels, a generator, battery storage, and a converter to meet the energy demands of a community load in Boumerdes, Algeria. The simulation and economic analysis performed using HOMER Pro provided valuable insights into the optimal configuration and operational dynamics of the system over a 15-year period. The PV + Generator + Battery + Converter configuration emerged as the most cost-effective solution, balancing moderate capital expenditure with the lowest net present cost (NPC) and operating costs, while also achieving a competitive levelized cost of energy (LCOE). This hybrid system effectively integrates renewable energy, ensuring a reliable and sustainable power supply while optimizing costs. The findings of this project demonstrate the viability and benefits of hybrid energy systems in meeting diverse energy demands, paving the way for more sustainable and resilient energy solutions in similar contexts.

General conclusion

This project report has comprehensively examined the potential and performance of hybrid energy systems within a microgrid framework. The study began by exploring the fundamentals of microgrids, their critical components, and operational modes, laying a solid foundation for understanding their role in modern energy systems. A detailed analysis of photovoltaic (PV) systems, particularly relevant to regions like Algeria, provided a technical basis for the simulations.

Simulations using Simulink demonstrated the effectiveness of integrating PV and battery systems into a microgrid, showing that hybrid systems significantly enhance load management and reliability. Further, a HOMER simulation evaluated a hybrid energy system comprising PV panels, batteries, and a diesel generator in Boumerdes, Algeria, over a 15-year period. The results underscored the long-term viability and efficiency of such systems in sustainably meeting community energy needs.

Overall, the findings suggest that well-designed hybrid energy systems can robustly manage energy demands and promote renewable energy use. Future research should focus on optimizing these systems for cost, scalability, and local energy policies. This report provides valuable insights and a solid foundation for advancing hybrid energy systems within microgrids, contributing to more resilient and sustainable energy infrastructures.

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